ARIZONA DEPARTMENT OF TRANSPORTATION

REPORT NUMBER: FHWA/AZ — 81/176

SULFUR-ASPHALT AND AGGREGATE MIXTURES

Prepared by:
R.A. Jimenez
W.R. Meier, Jr.

June 1981

Prepared for:
U.S. Department of Transportation
Federal Highway Administration
Arizona Division

SULFUR-ASPHALT AND AGGREGATE MIXTURES

by

R. A. Jimenez
W. R. Meier, Jr.

Report Number ATTI-81-2

Submitted to

The Arizona Department of Transportation
Highway Division
Phoenix, Arizona

Research Project - Arizona HPR-1-19(176)

Sponsored by

The Arizona Department of Transportation
In Cooperation With
The U. S. Department of Transportation
Federal Highway Administration

Arizona Transportation and Traffic Institute
College of Engineering
The University of Arizona
Tucson, Arizona

June 1981

00928

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/AZ-81-176		

4. Title and Subtitle	5. Report Date
Sulfur-Asphalt and Aggregate Mixtures	June 1981
	6. Performing Organization Code
7. Author(s) R. A. Jimenez and W. R. Meier	8. Performing Organization Report No. ATTI-81-2
9. Performing Organization Name and Address Arizona Transportation and Traffic Institute College of Engineering University of Arizona Tucson, Arizona 85721	10. Work Unit No. (TRAIS) 11. Contract or Grant No. HPR-1-19(176)
12. Sponsoring Agency Name and Address Arizona Department of Transportation 206 South 17th Avenue Phoenix, Arizona 85007	13. Type of Report and Period Covered Final June 1981 14. Sponsoring Agency Code

15. Supplementary Notes Prepared in cooperation with the U. S. Department of Transportation, Federal Highway Administration, from a study of Sulfur-Asphalt and Aggregate Mixtures. The opinions and conclusions are those of the authors and not necessarily of the Federal Highway Administration.

16. Abstract

This report is concerned with the evaluation of sulfur-asphalt and aggregate mixtures that would probably be used for construction by the Arizona Department of Transportation. Three aggregates used in highway paving were mixed with a 30/70 weight ratio of sulfur to asphalt blend and evaluated for Hveem and Marshall design properties. Additionally, one aggregate plus sulfur-asphalt mixtures was used to determine the effects of sulfur and/or anti-strip on resistance to debonding, effects of temperature on the value of tensile strength and elasticity, effects of aggregate moisture on debonding, and effects on fatigue life under repeated flexural stresses. In comparison with asphalt mixtures, it was found that adequate or higher stability values were obtained with the addition of sulfur; the use of sulfur reduced the retained strength in the debonding test; the addition of sulfur reduced the tensile strength but not the dynamic modulus of elasticity when compared at various temperatures; and the fatigue life of the asphaltic mixture was decreased with the addition of sulfur.

17. Key Words	18. Distribution Statement
Sulfur extended asphalt, asphaltic concrete mixture design, asphaltic concrete testing.	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

SULFUR-ASPHALT AND AGGREGATE MIXTURES

Synopsis

This report is concerned with the evaluation of sulfur-asphalt and aggregate mixtures that would probably be used for construction by the Arizona Department of Transportation. Three aggregates used in highway paving were mixed with a 30/70 weight ratio of sulfur to asphalt blend and evaluated for Hveem and Marshall design properties. Additionally, one aggregate plus sulfur-asphalt mixtures was used to determine the effects of sulfur and/or anti-strip on resistance to debonding, effects of temperature on the value of tensile strength and elasticity, effects of aggregate moisture on debonding, and effects on fatigue life under repeated flexural stresses. In comparison with asphalt mixtures, it was found that adequate or higher stability values were obtained with the addition of sulfur; the use of sulfur reduced the retained strength in the debonding test; the addition of sulfur reduced the tensile strength but not the dynamic modulus of elasticity when compared at various temperatures; and the fatigue life of the asphaltic mixture was decreased with the addition of sulfur.

INTRODUCTION

The oil embargo of 1973 indicated an impending shortage or controlled amount of asphalt being available for paving highways. Also, the amount of sulfur being produced in North America has been increasing at a very rapid rate. The use of sulfur as a binder has been known for many years and consideration for use in a mixture with asphalt was given by Bencowitz and Boe [1] as early as 1938. Sulfur is a liquid at a temperature between 121 and 149°C (250 and 300°F) which is within the range of temperatures for mixing, placing, and compacting asphaltic concrete. Within the past ten years there has been an intensive promotion for the use of sulfur as a modifier or replacement of asphalt in paving mixtures. The encouragement for using sulfur in asphaltic mixtures has been based on economic factors, conservation of asphalt, reduction of air pollution, and seemingly the resultant being an improved material [1-23].

The objectives of this investigation were to determine the characteristics of three aggregates when mixed with a 30/70 weight ratio of sulfur to asphalt and evaluated using the standard Hveem and Marshall procedures. Additionally, the effects of variations of compaction temperature and moisture in the aggregate on Marshall stability and on resistance to debonding of the binder were to be investigated. Certain aggregate-binder mixtures were tested to determine tensile and fatigue properties at various temperatures. As can be seen from the stated objectives, the principal aims of the study were to characterize three aggregate blends when mixed with sulfur-extended asphalt (SEA).

REVIEW OF LITERATURE ON SULFUR-EXTENDED ASPHALT

Prior to initiating the work for evaluating SEA-aggregate mixtures, a literature survey of the field was made. The review to be presented in the following paragraphs is an updated concept of the use of sulfur in paving which has come about from our recent experiences and reevaluations of earlier readings on the use of SEA mixtures.

Sulfur is a natural element which is a solid at ambient temperature, melts at about 121°C (250°F) and as a liquid its viscosity decreases as temperature rises to about 149°C (300°F) and then the viscosity increases very rapidly with further increase in temperature [3]. Elemental sulfur exists in several allotropic forms [24]. Upon melting and following cooling, it goes into a monoclinic crystal with density of 1.96 and then passes slowly into rhombic crystals having a density of 2.06. Asphalt is also a liquid at temperatures between 121-149°C (250-300°F) and thus facilitates its blending with sulfur at these temperatures; however, the heating of sulfur above 149°C (300°F) is not recommended because of the production of toxic hydrogen sulfide.

The modification of paving mixtures with SEA is attributed to three factors resulting from mixing sulfur and asphalt. Kennepohl *et al*. [5] and Pickett *et al*. [15] indicate that sulfur will dissolve in asphalt from 12-23 percent by total weight; however, Gaw [6] suggests that there is not a true solution action since the effects of sulfur on increasing penetration values was temporary and lost after seven days of storage at 75°C (167°F) or by ten minutes of ultrasonic vibration and so such mixtures should be called emulsions. We note the storage temperature of

75°C (167°F) is one that is reached in pavements located in southern Arizona. Kennepohl *et al*. [5, 9, 20] have emphasized that the mixing of hot asphalt and sulfur in their studies used a high rate of shear, but it would seem that hand stirring of a sulfur-asphalt blend would be sufficient to "dissolve" less than 20 percent sulfur in hot asphalt.

From the above it is implied that SEA of greater than 20 percent sulfur will contain crystallized sulfur upon cooling. The size of the solid sulfur would depend upon the size of droplet created during mixing and the degree to which the droplets will combine to increase in size. The size of solid sulfur particles in a paving mixture will affect the way in which sulfur may modify the properties of the compacted material. We have found that asphalt paving mixtures meeting standard design criteria have an asphalt film thickness of about 8 microns (3×10^{-4} in.) when we calculate the aggregate surface area using the California factors [25]. Sulfur particles that remain in suspension and are smaller than say 6μ (2×10^{-4} in.) will serve to increase the binder volume and change its viscosity. The size of the liquid sulfur droplet at the time of mixing would be affected by the rate or speed of the mixing and thus the extent to which the sulfur will perform within the asphalt film.

In a cooled paving mixture, solid sulfur may also exist within the air void space, that is, as a coated or uncoated aggregate. The amount of sulfur in this stage depends upon the amount of sulfur used, upon the shear rate used in mixing, upon the amount of time available for the heavier sulfur to settle and separate prior to mixing with the hot aggregate, and perhaps as Gaw [6] suggested, the amount of time since the compaction of the mixture.

Most of the reports on the use of sulfur in paving mixtures have emphasized improved physical properties on freshly prepared specimens when compared with asphaltic mixtures without sulfur.

In 1974, Deme [3] reported on properties of sand-asphalt-sulfur mixtures in which weight components were 4:14:82 of asphalt, sulfur, and sand respectively. These mixtures were extremely fluid at placement temperatures in that at a temperature of 138°C (280°F) the slump was 25.4 cm (10 in.). These mixtures of themselves were not of the kind we were investigating; however, three comments in the report are of general interest:

1. Ottawa sand was wetted by the asphalt regardless of sequence for mixing; that is, asphalt and sand first and then adding sulfur, or sulfur and sand first and then adding asphalt, or sulfur and asphalt first and then adding sand. However, there were always traces of sulfur with direct contact with the sand.
2. In the cooled mixture, the sulfur filled all the void spaces by what appeared to be sulfur granules rather than a solid mass.
3. ". . . we found that after applying over 10 to 20 Marshall hammer blows on a single specimen face the mix structure was disrupted by (the) additional compaction, resulting in a reduction in mix stability".

In opposition to Item 1 above, Bean *et al*. [20] stated that the aggregate used in their study showed a preferential coating of sulfur instead of asphalt.

Effects of sulfur on design properties as evaluated by standard Marshall or Hveem procedures are difficult to determine from the literature surveyed. The reasons for this are as listed below:

1. Some of the sulfur-asphalt blends were designed to perform as an emulsion and thus contained emulsifying agents [7, 11].
2. Compaction of the specimen was achieved with the Marshall hammer using 30 or 35 blows per face [7].
3. Marshall compacted specimens were used for determining Hveem stability [15].
4. Variable storage time of compacted specimens prior to testing for stability [7, 11].

There is a consensus that more than 20 percent of sulfur in the SEA mixture is required to improve physical properties of paving mixtures [9, 13, 23]. The amount of sulfur used in SEA has been between 30 and 50 percent of the blend. It would seem that if the 20 percent of sulfur that is "dissolved" in asphalt contributes to improved performance of SEA paving mixtures, then it does so by allowing the surplus over 20 percent to perform as a solid in the paving mixture.

The research sponsored by Gulf Oil of Canada and reported by Kennepohl and associates [5, 8, 9, 18, 19, 20] attribute improved mixture characteristics in the following areas for SEA mixtures:

1. Higher Marshall stability.
2. Greater resistance to rutting but also good low temperature performance with less cracking.
3. Undergo less fatigue damage.

The above improvements of SEA concrete over asphaltic concrete might indicate a lessening of total pavement thickness. However, a pavement design analysis performed by Lytton _et al_. [10] using the VESYS IIM procedure indicated ". . . that sulphur-asphalt systems appear to be superior to asphaltic concrete in reducing rutting and preserving a high serviceability index but tend to be more susceptible to fatigue cracking than conventional asphaltic concrete". The susceptibility to fatigue cracking of SEA concrete could be counteracted by an increase in surface course thickness and thus affect total cost.

The above paragraphs have dealt principally with the physical or mechanical properties of laboratory prepared SEA specimens evaluated at an early age. Fromm et al. [18] states that SEA mixtures have improved resistance to stripping or debonding over straight asphaltic mixtures: therefore, improved durability. The aspect of improved mixture durability with reference to mechanical properties was addressed by Lee [12] and Al-Otaishan et al. [21]. Lee exposed Marshall specimens to natural weathering and found ". . .the resilient modulus and tensile strength of sulphur-asphalt concrete increased with weathering; however, both resilient modulus and tensile strength of the weathered sulphur-asphalt concretes were lower than those of asphalt concrete without sulphur".

Al-Otaishan [21] obtained cores from various in-service pavements and compared certain physical properties obtained from SEA mixtures with those for the control asphaltic mixtures. Comparison of values for the cores showed the following:

1. Marshall stability; asphalt cement (4.80%) higher than for SEA (5.65%).
2. Creep compliance; SEA higher than for asphalt cement.
3. Fatigue resistance; asphalt cement better than for SEA.

Going on from the stability and durability of SEA concrete to mixture proportioning, a review of the literature and experience by both Izatt [16] and Smith [17] suggests that the design SEA binder content by weight be equal in volume to the asphalt content being replaced. The amount of sulfur in the blend may range from 30 to 50 percent by weight. Since the amount of sulfur over 20 percent will perform as filler aggregate, it is suggested that the 30 percent sulfur be used with the denser gradations of aggregate.

Before leaving the review of SEA concrete mixtures, we must look at the durability of the SEA binder as it might affect the durability of the total paving mixtures. Bencowitz and Boe [1] and Lee [2] showed the aging characteristics of the base asphalt were impaired by the addition of sulfur. Since Bencowitz used a two-hour cooking of the sulfur asphalt mixture and Lee used cold powdered sulfur, neither of which is presently a used procedure, Jimenez and Stokes [22] evaluated the effects of heat and air on the viscosity of SEA blends. The exposure was that of the original RTFOT and viscosity was determined at three temperatures. The study indicated that aging of SEA destroyed the initial beneficiation of the sulfur so that the properties of the aged SEA blend were comparable or worse than those of the base asphalt.

It is apparent that there is much to be learned about SEA mixture, especially with reference to durability. It is of concern that the SEA blends have shown impaired resistance to aging and if SEA is to be substituted in an equal volume of pure asphalt, then the resulting asphalt film thickness will be less than for the base asphaltic mixture.

MATERIALS USED

As indicated earlier, standard mix design procedures were to be followed on aggregates from three pits that serve ADOT as sources for paving mixtures. The primary asphalt used was an AR-2000 although some testing was performed with an AR-4000. The sulfur blend was held constant at a 30/70 sulfur to asphalt weight ratio.

Materials

Sulfur

The powdered sulfur used was of a commercial source with 99.5 percent purity. The particle size distribution was such that 92 percent passed the No. 30 sieve and 6 percent passed the No. 200 sieve. The specific gravity of the sulfur was determined by ASTM D70-70 for semisolid bituminous materials using a pycnometer. The weight measurements were made at 25°C (77°F) after having cooled for 24 hours since melting. The value obtained was 1.996. A chemical index [24] gives values of specific gravity for sulfur ranging between 1.96 to 2.06 depending on its crystalline form.

Asphalts

The majority of the SEA blends were made with AR-2000 since the literature survey indicated the most beneficiation from the sulfur would come with the softer asphalts. However, SEA with AR-4000 was used in mixture designs of the three aggregates. The characteristics of these asphalts according to specifications [26] are shown in Table A-1. The specific gravity of both asphalts was determined to be 1.020 at 25°C (77°F) which compared very favorably with the measured value of 1.195 for the 30/70 SEA blend with the AR-2000 which will be identified as SEAR.

Aggregates

The physical properties of the basic aggregates are listed in Table A-2. The aggregate from Pit #1 came from the Salt River in Phoenix, that from Pit #2 came from the banks of the Santa Cruz River in Tucson, and that from Pit #3 was a blend of crushed basalt and field sand from the Holbrook area. It is noted that the basic gradations conform to a maximum density distribution and thus the lowest recommended sulfur content was justified for this study. All three aggregates had adequate sand equivalent values and thus should show good resistance to debonding. In order to check the alleged improvement to resistance to stripping by the addition of sulfur, the aggregate blend in Pit #2 was modified to yield a sand equivalent of 33.

The effective specific gravity values for the aggregates are shown for mixtures with both AR-2000 and AR-4000.

The surface area of the aggregate blends was calculated using the surface area factors for the Hveem procedure [25].

TESTS AND TEST PROCEDURES

Tests and test procedures are described in a general form in the following paragraph. Detailed descriptions are given in referenced standards.

Mixing Sulfur and Asphalt and Aggregate

A review of the literature showed a great variety in the method of mixing asphalt and sulfur and often specific details were not given.

The mixing procedure for combining sulfur and asphalt was held constant with reference to batch size and other factors believed to affect the resulting mixture. The batch size was held to approximately 1,000 g of total mixture, asphalt was held to constant temperature in a metal container (1.4 liter or No. 10 fruit juice can) placed in a 135°C (275°F) oil bath. The sulfur was melted and held in a sealed glass beaker placed in a 135°C (275°F) forced draft oven. The hot sulfur was added to the asphalt and stirred with a two-bladed laboratory mixer that had an unloaded speed of 1700 rpm for a period of three minutes. Then the container was dried on the outside and placed in a 135°C (275°F) oven. The oil bath was built with a portable hood having a transparent door and exhaust fan, thus minimizing the need for breathing masks during the mixing operation.

The 1000-g batch of SEAR was sufficient for producing three standard sized specimens at four binder contents and mixture for the determination of the Rice specific gravity.

The aggregate to be mixed with the SEAR was brought to temperature in a 121°C (250°F) oven. (At 135°C the sulfur fumes during mixing were too oppressive.) The amount of aggregate per batch was sufficient to yield three specimens plus about 1000 g of loose mixture. Prior to each addition of binder to the hot aggregate, the SEAR was stirred vigorously with a spatula to minimize separation or settling of the sulfur.

The addition of the SEAR to the aggregate was done as quickly as possible and mixing was done with a 10-quart Hobart food mixer using a type D wire whip. After approximately 1½ minutes of mixing, the sulfur-asphalt-aggregate was dumped into a large hot flat metal pan to check for the uniformity of the material and additional hand mixing was done if necessary.

Approximately 1200-g samples were taken from the pan and placed into one-gallon pails to be sealed and placed in a 121°C (250°F) forced draft oven. After one hour in the oven, the mixture would be at the desired compaction temperature of 121°C (250°F).

Standard Compaction and Test Procedures

Hveem Method of Design

Compaction and testing of specimens for the Hveem mixture design method followed the basic procedures described by the Asphalt Institute [27] and using the California kneading compactor which is also known as the Triaxial Institute (T.I.) compactor. Specimens were formed in triplicate and extruded from the mold within ten minutes after applying the leveling load. Density and height measurements were performed the day following compaction. After essentially seven days of storage at 25 ± 2°C (77 ± 3°F), the specimens were tested at 60°C (140°F) for Hveem stability and cohesiometer value.

Marshall Method of Design

Similar to the Hveem method of design, the compaction and test procedures used were basically those described by the Asphalt Institute manual [27]. The specimens were compacted at a temperature of 121°C (250°F) with 75 blows on each face using a mechanized compactor. The compacted mixture was treated the same as for the Hveem specimens except that it was brought to the test temperature by immersion in water at 60°C (140°F) for a period ranging between 30 to 40 minutes.

Variations of Compaction Temperature

At times a premature pavement surface failure has been attributed to low construction density which may have been caused by low compaction temperature. The effects of compaction temperature on a sulfur-asphalt-aggregate mixture were examined using two tests. The mixture proportions were based on earlier tests on Pit #1 and used an SEAR content of 5.6 for Marshall tests and 5.1 percent for durability. The tests used to determine the effects of the compaction variation were the University of Arizona Debonding developed by Jimenez [28] and the Marshall; the compaction temperatures were 107, 121, and 135°C (225, 250, and 275°F).

Debonding Test

The Debonding test is used to evaluate the resistance to stripping of a compacted asphaltic mixture when subjected to a dynamic and repeated pore water stressing condition. Standard sized specimens are compacted with a vibratory kneading compactor (VKC). A control set of three specimens is tested for tensile strength at 25°C (77°F) using a double punch procedure. The exposed set is subjected to a repeated pore water pressure alternating from 35.5 - 206.7 kPa (5 - 30 psi) for 5800 cycles in ten minutes at a temperature of 50°C (122°F). After cooling in water at 25°C (77°F) the stressed set is tested for retained tensile strength.

The compacted specimens were measured for height and density in the same way as for stability testing and the evaluation for debonding was made seven days after compaction.

Marshall Test

The Marshall stability and flow values were determined in the same manner as described earlier.

Using Anti-strip and Sulfur as Bonding Additives

The literature reviewed implied that sulfur improved a mixture's resistance to the effects of water; additionally, an experimental sulfur-asphalt pavement was designed to contain an anti-strip agent in the mixture. To check the effects of sulfur and in combination with an anti-strip agent, the aggregate of Pit #1 was mixed with asphalt, asphalt plus anti-strip, SEAR-2000, and SEAR-2000 plus anti-strip and the results of treatment were evaluated at three binder contents using the Debonding test.

In the development of the Debonding test, a limited amount of data were used for comparing retained strength values obtained with the immersion compression test of ASTM D 1075. As noted in Reference [28], the Debonding test yielded equal retained strength values below about 50 but higher than those obtained from the imemrsion compression test at the higher levels. More recently, Scott and Ritter [29] of ADOT reported on an evaluation of the Debonding test. In comparing the retained strength obtained by the two mentioned procedures, the report had the following linear equation.

$$\%S_R \text{ by } I^-C = 8.93 + 0.82\ (\%S_R \text{ by Debonding})$$

It appears that the Debonding test yields retained strength values approximately 1.20 higher than those obtained from the immersion compression test.

As noted in Table 2, the aggregate from Pit #1 had a relatively good sand equivalent value and thus should have good resistance to debonding. The aggregate from Pit #2 was modified as shown in the table to have a reduced sand equivalent value of 33 and then used in this portion of the investigation.

Variation on Test Temperatures for Tensile Tests

The use of sulfur in paving mixtures had been recommended for improving the temperature susceptibility of the resilient modulus of elasticity [8]. This effect was examined for the three aggregate sources containing AR-2000 and also SEAR-2000 at test temperatures of -5, 10, and 25°C (23, 50, and 77°F).

The indirect tensile test of the double punch procedure was used to obtain a measure of tensile strength at those temperatures.

A measure of the value of dynamic modulus of elasticity was obtained using a repeated double punch loading. The procedure has been described by Jimenez [29] and results were compared with those obtained with the Chevron procedure for resilient modulus by White [30]. In this procedure the dynamic modulus of elasticity is calculated from a cycled tensile stress varying from 34.5 to 137.8 kPa (5 to 20 psi) at a frequency of 11.5 Hz and the measured repeated radial dilation at mid-height of a standard sized specimen.

Variation of Moisture Content in Aggregate

Construction problems have been associated with moisture in the aggregate at the time of mixing and compaction. A portion of the study was to investigate the effects of moisture in an aggregate upon the Marshall stability and the Debonding test results.

Our review of the literature showed only one report concerned with a laboratory investigation on effects of moisture in the aggregate at the time of mixing on properties of asphaltic concrete. This report by Sonderegger [32] presented a procedure in which hot damp coarse aggregate was mixed with hot fine aggregate that had already been mixed with hot asphalt cement. The procedure described by Sonderegger was not thought to be adequate for our purpose, especially since the maximum amount of moisture retained in the mixtures was about 0.4 percent.

Various trials were made to have moisture retained in an aggregate blend at a temperature near 121°C (250°F). The following procedure was used for this study. Approximately 4,500 g (10 lbm) of the moistened aggregate blend at 2 percentage points above the final estimated moisture content was placed in a metal pan which was covered with a plastic sheet and allowed to set for 24 hours. The pan containing the aggregate was then placed in a 6-quart pressure cooker that had 1000 ml of water. The sealed pressure cooker was then pressurized to 103.3 kPa (15 psi) with air which corresponds to a steam temperature of 121°C (250°F). The cooker was heated on an electric hot plate until a vigorous release of steam was seen and then heating with slight jiggling of the pressure regulator was continued for 45 minutes more.

Pressure in the cooker was released as quickly and safely as possible (within 30 seconds) and the cover removed. The hot moist aggregate went directly to mixing with SEAR-2000 at 135°C (275°F) for approximately 1½ minutes. No measurement of aggregate temperature was attempted. Samples of the mixture were weighed for the corresponding test specimen and placed in a metal pail to be sealed and placed in a 121°C (250°F) oven. A sample of about 500 g was taken for moisture content determination and recording. Specimens were compacted, stored, and tested as described earlier for Marshall and Debonding values.

A limited amount of evaluation was performed on the moist aggregate brought to a temperature of 93°C (200°F) prior to mixing with the hot SEAR-2000.

Flexural Fatigue Tests

For the past 20 years, the importance of an asphaltic concrete's resistance to flexural fatigue has been recognized since most highway pavement failures have been attributed to fatigue cracking. Fatigue testing was performed using the Deflectometer [30, 33]. In this device a 45.7-cm (18-in.) diameter asphaltic concrete slab is fixed about its periphery, is given a uniform fluid pressure support, and is given a repeated sinusoidal load at a frequency of 11.5 Hz distributed over a circular area on the top center of the slab. The Deflectometer is a constant stress loader and fatigue life of a mixture is expressed in terms of tensile radial stress vs. number of repetitions to cause failure. Variations in stress are effected by using specimens of different thickness or by varying the area of the load disc.

Fatigue tests were performed on specimens made with aggregates from Pit #1, containing either AR-2000 or the corresponding volume of SEAR-2000, and at temperatures of 25°C (77°F) or 5°C (41°F).

TEST RESULTS AND DISCUSSIONS

The testing program was developed around goals of characterizing certain SEAR mixtures for construction and performance behaviors. The aggregate sources, proportion of sulfur to asphalt, and grade of asphalt used were set principally from usage consideration.

Aggregate Characteristics

Measurements for particle size distribution, sand equivalent, and effective specific gravity of the aggregates are shown in Table A-2. The data shown indicate the materials to be generally of good quality. An objection to the blends might be that the gradations approached yielding a maximum density and thus limiting the amount of binder in consideration of durability, and especially if the excess sulfur over the 20 percent soluble in asphalt would crystallize and act as a void filler.

Hveem and Marshall Tests

Test results obtained with the Hveem and Marshall design methods for the three aggregate sources are listed in Tables A-3, A-4, and A-5. The Hveem method was used on mixtures containing AR-2000 without sulfur but both Hveem and Marshall methods were used for mixtures with SEAR combinations with AR-2000 and AR-4000. The binder content is expressed as a percent by total weight (BTW) of mixture. Since the sulfur is twice as heavy as asphalt, the SEAR listings also show the asphalt content which would have an equal volume of SEAR. For example, if the SEAR content is 5.0 percent by weight, the SEAR volume would be equal to the volume of asphalt at 4.3

percent. This same reduction of SEAR content has been made for showing the effects of SEAR content on air void and stability values in Figures 1, 2, and 3.

Pit #1 Test Values

Figure 1 presents graphs of air void and stability values listed in Table A-3.

Hveem Method. The density data show that the SEAR-2000 specimens were heavier than the AR-2000 ones; however, the air void curve of Figure 1 shows no appreciable difference when the binder content is expressed in an equal volume basis. The SEAR-4000 specimens had essentially the same density and so also the same air void content as did the specimens made with SEAR-2000.

Figure 1 clearly shows the much improved Hveem stability value when sulfur was added to the AR-2000 asphalt. The stability value for the SEAR-4000 mixtures was just slightly greater than those for the SEAR-2000 material.

It seems that the improvement in stability value was brought about by the free sulfur acting as aggregate to increase the frictional resistance of the compacted mixtures. This increase in stability is attributed to the free sulfur since cohesiometer values were not significantly affected by addition of sulfur.

If the design SEAR content would be selected to yield an air void content of 4 percent, both SEAR-2000 and SEAR-4000 mixtures would have a binder content of 4.1 percent by total weight. This relatively low amount of binder comes about because of the dense gradation of the aggregate. The durability of the mixture would be suspect, especially when one considers that the pure asphalt content would be about 2.9 percent.

Marshall Method. As mentioned earlier, one of the objectives of the study was to develop mixture design data on SEAR mixtures, and as a consequence, there were no tests performed on straight asphalt mixtures with the Marshall procedure.

In Figure 1 it can be seen that the air void content for the Marshall specimens is approximately two percentage points higher than for the Hveem specimens and that asphalt grade had an effect on the void content of the Marshall specimens.

The Marshall stability was generally about 8.88 kN (2000 lbf); and flow values were generally below the recommended maximum of 16 units according to the Asphalt Institute [27].

Basing the design SEAR content on 5 percent voids, it is noted that the binder content would be 5.3 percent by total weight for the SEAR-2000 and 5.0 percent for the SEAR-4000 mixture.

Pit #2 Test Values

The aggregate from this source was finer graded than that from Pit #1 in that 9 percent was retained on the 9.5 mm (3/8 in.) sieve. Test results are discussed with reference to Table A-4 and Figure 2.

Hveem Method. The same general behavior as for Pit #1 is noted for the AR-2000 mixtures in Figure 2 in that the same air void content curve was obtained for the specimens with or without sulfur and also the addition of sulfur increased the Hveem stability values.

The specimens made with SEAR-4000 had higher void content and may have caused the lower stability values than those with SEAR-2000.

It appears that the addition of sulfur may have increased the already acceptable cohesiometer value for the AR-2000 specimens.

If the binder content is to be selected on the basis of 4 percent voids in the SEAR-2000 mixture, then it would be approximately 6.5 percent by total weight (5.5 ÷ 0.85 = 6.5).

Marshall Method. From Figure 2 it can be seen that there is not much difference in air void content for the specimens containing SEAR-2000 or SEAR-4000. As for the mixtures of Pit #1, the Marshall specimens had higher air void content by approximately 3 to 4 percentage points. These higher air void contents and higher differences as compared with the values for the Pit #1 specimens are most likely due to the finer gradation of the aggregate and these differences could have been anticipated.

Marshall stability and flow values were within recommended limits and based on an air void value of 5 percent, the corresponding SEAR-2000 content would be more than 7.5 percent which is on the downslope of the stability curve.

Pit #3 Test Values

The aggregate came from the Holbrook area, it had the coarsest gradation, and the plus #16 sieve size material was a basalt with a high specific gravity of 2.99. Figure 3 presents curves for air void content and stability values listed in Table A-5.

Hveem Method. The effects of SEAR-2000 content on air void and Hveem stability values were similar to those caused by AR-2000 content.

The use of SEAR-4000 resulted in higher air void, higher stability, but equal cohesiometer values when compared to those obtained with SEAR-2000.

If the design SEAR-2000 content is based on an air void value of 4.0 percent, then the binder content would be approximately 4.0 percent. Again as for the Pit #1 SEAR mixture, the binder content would be considered to be extremely low in consideration of durability.

Marshall Method. The curves of Figure 3 show that adequate air void content and stability values were obtained with both SEAR-2000 and 4000, and Table A-5 lists approximately equal flow values for both mixtures.

If the design SEAR-2000 content is set at 5.0 percent, the air void value would be about 5.0 percent, the stability would be about 7.77 kN (1750 lbf), and flow would be 9 units. The Marshall design criteria are met with the above values; however, we believe the binder content is too low as indicated above for the Hveem design method.

In the design of asphaltic paving mixtures, a basic concept is to use as much asphalt as possible without undue sacrifice of stability. Our experiences with sampling pavement surfaces that have become rutted or deformed have shown a common denominator that air void content was equal to approximately 2 percent. As a consequence, we select design asphalt contents for paving mixtures at a value that will preclude the mixture reaching a final air void content of 2 percent in the pavement.

Asphalt paving technologists recognize that the Hveem (T.I.) compaction yields higher densities than those obtained by the 75-blow Marshall procedure. Examination of the density data presented in Tables A-3 to A-5 shows this difference. In the tests using Pit #1 aggregate in which only one binder content was used, we selected that value which yielded 3.0 percent air voids for the Hveem procedure and 5.0 percent for the Marshall method.

Variation of Compaction Temperature

The results of varying the compaction temperature on Marshall and Debonding test values are shown on Table A-6. The SEAR content was varied for the two tests because of the desire to approach a 3.0 percent air void content for the Debonding test and 5.0 percent for the Marshall.

The table shows that all Marshall stability values were above 6.66 kN (1500 lbf) and the Debonding retained strength values increased from 85 percent at the low compaction temperature to 100 percent at the high compaction temperature. The high values of retained strength are attributed to the good quality of the aggregate.

Computations for analysis of variance (ANOVA) followed procedures given by Hicks [34] and are shown on Table A-6-1 for the test results. The analyses indicate that the variations in compaction temperature had no significant effects on Marshall stability nor on Debonding air void content; but it did affect the Marshall air void content, and both of the Debonding wet and dry strength values.

Anti-strip and Sulfur as Bonding Additives

Results of the Debonding test on asphaltic mixtures containing an anti-strip, sulfur, and a mixture of anti-strip and sulfur are listed on Table A-7. Examination of the data indicates that as might be expected the retained strength of the four mixtures generally increased as the binder content increased; however, it is noted that the control mixture with AR-2000 had very high retained strength values and the need for an anti-strip additive was not warranted. A closer look at the data also shows that the retained strength values for the mixtures containing sulfur were generally lower than those without sulfur.

The above seeming effect of sulfur on mixture strength suggested looking at effects on dry and wet strength caused by sulfur, anti-strip, and binder content expressed as levels of low, medium and high. In order to satisfy the requirements for performing an analysis of variance, the binder content variable was described as low, medium, and high since these were not exactly equal for the three mixtures containing sulfur and/or anti-strip. However, examination of the binder content data shown on Table A-7 shows that on a volume basis the binder contents for the sulfur mixtures are equal but vary by a very small value (0.2 percent) with the mixture without sulfur. The results of the ANOVA are shown in Table A-7-1 and indicate that only sulfur had an effect on the values of wet and dry strengths. Another look at the data on Table A-7 will show that the lowest wet strength at any one binder content was obtained for a sulfur mixture and also the same lowest dry strength was found for a mixture containing sulfur.

Since the aggregate of Pit #1 was relatively clean and with no apparent need for an anti-strip additive, the aggregate of Pit #2 was modified to have a low sand equivalent value without appreciable change in gradation from the original. The differences can be seen in Table A-2.

The data for the Debonding test for the modified Pit #2 aggregate are shown on Table A-8. The effects of sulfur on wet and dry strength were as shown above for the Pit #1 aggregate; that is, the lowest strengths for any one of the corresponding binder content were for a sulfur mixture.

In Figure 4, the curves represent the effects of binder content and binder type on the retained strength values for the two aggregates tested. From the figure it can be seen that the sulfur mixtures generally had the lower retained strength values. Additionally, it is indicated that there was no adverse effect upon combining the anti-strip with the sulfur, in fact, it had a most beneficial effect for the low sand equivalent aggregate. The data strongly suggest that the addition of sulfur to the mixtures tested impaired their resistance to debonding.

Test Temperature Effects on Tensile Properties

A review of the literature had indicated that the temperature susceptibility of the resilient modulus of a mixture would be improved with the addition of sulfur [8]. The aggregates from the three pits were mixed with asphalt AR-2000 and also with SEAR-2000 at binder contents that would yield approximately optimum and equal air void content for each source. The compacted specimens were evaluated for dynamic modulus of elasticity first and then loaded to failure to determine their tensile strength. Data for this series of testing are listed in Table A-9 and a visual effect of temperature and sulfur on modulus and tensile strength is presented in Figures 5 and 6.

The curves of Figures 5 and 6 have been drawn by "eye" and thus reflect a bias in their location. The analysis of variance results presented in Table A-9-1 eliminate the bias and indicate that only temperature had a significant effect on dynamic modulus of elasticity E_D, thus neither the aggregate source nor presence of sulfur had an effect on the value of E_D. As mentioned by Jimenez in Reference [35], there is a suspicion that at the low repeated tensile stresses used in the test for E_D, the resulting strains were too low to be influenced by the aggregate in the specimen.

The ANOVA of Table A-9-1 also shows that temperature, aggregate source and the addition of sulfur all had an effect on the tensile strength. It is obvious and was expected that as the temperature decreased the tensile strength increased as was the case for the value of E_D. In this portion of the study it was again shown that the tensile strength was decreased when using sulfur. Although the volume of binder was the same for corresponding mixtures of AR and SEAR, the quantity of asphalt was less for the sulfur mixtures. An apparent loss in tensile strength was also shown by Kennedy _et al_. [9] with Figure 7.

The results of the Newman-Keuls test [34] shown in Table A-9-1 indicate that the tensile strength for Pit #2 was significantly lower than that for Pits #1 or #3.

In the study of Reference [31], White developed an equation relating the resilient modulus, M_R, obtained by Chevron to the dynamic modulus obtained using the Jimenez [30] procedure. The relationship is expressed as follows:

$$M_R = 2.29\ E_D + 168\ (\text{ksi}) \qquad (1)$$

Using this equation we obtain values of resilient modulus for the three aggregate sources tested at 25°C (77°F) ranging from 4,065 to 4,237 MPa (590,000 to 615,000 psi) when mixed with SEAR-2000. Kennedy and Haas [19] report values of M_R for a 30/70 SEAR-limestone mixture ranging between 3,445 to 6,201 MPa (500,000 to 900,000 psi); however, no reference of temperature, frequency of loading, nor loads are given. Also, Al-Otaishan and Terrel [21] showed values of M_R for 30/70 SEAR pavement cores tested at 20°C (68°F) by Texas A & M University and the University of Washington. The values of M_R obtained by Texas A & M ranged from 5,650 to 6,408 MPa (820,000 to 930,000 psi) and for the same pavement the University of Washington obtained values ranging from 3,445 to 3,789 MPa (500,000 to 550,000 psi). The values for repeated load and frequency were not given by Al-Otaishan.

Effects of Moisture in Aggregate

The results obtained in this portion of the study do not seem to be those one might have expected without having gone through the test program. As indicated earlier, the hot moist aggregate was mixed with the hot SEAR-2000 and the mixture sampled for moisture content. The weighed portion to make a specimen was placed in a metal can, sealed, and placed in a 121°C (250°F) oven.

At the time of mixing, it was noted that the mixture was brown in color and there was incomplete coating of the aggregate. Also after the specimen had been compacted and extruded, it was weighed periodically during the seven days of storage prior to testing. It was noted that there was no weight loss during the seven-day period of storage.

Examination of the internal portion of a specimen after testing to failure indicated that in general good coating of the aggregate had been obtained.

It would appear that whatever moisture was in the aggregate at the time of mixing was lost by the time the specimen was formed and that the compaction process completed or improved the coating of the aggregate.

Table A-10 lists the results obtained for both the Marshall and Debonding tests when mixing was performed at 121°C (250°F). The batch of aggregate prepared for mixing was sufficient to make three specimens only, and as a consequence, in the Debonding test a second batch had to be prepared to obtain strength values for both "wet" and "dry" conditions. However, it was impossible to duplicate moisture content for both sets of specimens. In order to obtain values for retained strength, plots of both wet and dry strength vs. moisture content were drawn and the corresponding strengths compared at equal moisture content. The generalized curves of results obtained for both the Debonding and Marshall tests are shown on Figure 8. As noted earlier, it is surmised that the effects of mixing moisture were lost by the time the specimens were tested.

Table A-11 presents the data obtained for the Debonding test when mixing was performed at 95°C (200°F). These results are similar to those obtained when mixing was performed at 121°C (250°F).

Fatigue Testing

The Deflectometer produces a crack pattern on an 45.7-cm (18-in.) diameter slab of asphaltic concrete that resembles alligator cracking in a pavement [33]. This device is a constant stress flexure fatigue tester.

The data presented in Table A-12 show values obtained from testing AR and SEAR mixtures at 5 and 25°C (41 and 77°F). The fatigue equations, $\sigma_T = I_o N^{-b}$, relating flexural tensile stress to number of repetitions to cause failure show that there was not much difference in the slope (b) of all four lines shown in Figure 9. However, the intercept values (I_o) for the asphalt and sulfur mixtures tested at 25°C (77°F) are different while those for the mixtures tested at 5°C (41°F) are basically not different.

If I_0 values (tensile strength at one repetition) are compared at the two test temperatures, then it is seen that the sulfur mixture was more temperature susceptible than the asphalt only mixture. This same conclusion is obtained when comparing double punch tensile strengths between -5 and 25°C (23 and 77°F). Specific data points are shown in Table 1.

Table 1. TEMPERATURE EFFECTS ON TENSILE STRESS DIFFERENCES FOR AR AND SEAR MIXTURES

Binder	Test	Test Temperature, Range °C	Stress Difference, psi	Greater Temperature Susceptibility
		Pit #1		
AR-2000	Fatigue, I_0	5 to 25	2383	no
	D.P. σ_T	-5 to 25	393	no
SEAR-2000	Fatigue, I_0	5 to 25	3883	yes
	D.P. σ_T	-5 to 25	428	yes
		Pit #2		
AR-2000	D.P. σ_T	-5 to 25	347	no
SEAR-2000	D.P. σ_T	-5 to 25	376	yes
		Pit #3		
AR-2000	D.P. σ_T	-5 to 25	355	no
SEAR-2000	D.P. σ_T	-5 to 25	427	yes

From Tables A-9 and A-12 one notes a difference in values for dynamic modulus of elasticity. This variation is attributed to differences in the theoretical analyses for calculating stress and strain and perhaps more importantly to the level of stress applied to the specimen. This difference in modulus is comparable to that discussed previously between double punch dynamic modulus and the resilient modulus obtained with the Chevron procedure.

CONCLUSIONS

The effects of incorporating sulfur into standard asphaltic mixtures has been investigated. The results obtained must be viewed from the position that the sulfur-asphalt blend was fixed at a weight ratio of 30/70 sulfur to AR-2000 or AR-4000, and also to the source and gradation of aggregates. The conclusions presented below are warranted for the materials tested and are based upon results obtained with the various test procedures of which some have not been standardized but whose relative values are recognized. It is to be noted that all specimens were tested at least seven days after compaction.

1. Some of the sulfur in the binder crystallizes and appears as a mineral aggregate in a SEAR paving mixture.
2. The addition of sulfur generally increased the Hveem stability but had no apparent effect on the cohesiometer value for mixtures with AR-2000.
3. Marshall stabilities were all above values specified for design as were the cohesiometer values.
4. It is noted that due to the dense gradation of the aggregates, the design binder content for both asphalt and SEAR were considered to be on the low side with reference to durability of the mixtures.
5. The Pit #1 aggregate SEAR mixtures when compacted at the various temperatures did not show significant differences in Marshall stability nor on retained strength determined with the U. of A. Debonding test.

6. The investigation of using sulfur to improve the resistance to debonding of a mixture with the aggregate from Pit #1 showed that sulfur mixtures had lower retained strength values than those without sulfur; however, because of the quality of the aggregate the absolute values of the retained strength were considered adequate. The addition of sulfur lowered the tensile strength of all mixtures. The Debonding results obtained with mixtures of a modified Pit #2 having a sand equivalent value of 33 indicate the same trend shown above but to a greater degree in that there were substantial losses in tensile strength and retained strength for the sulfur mixtures. Both sets of data suggested that the addition of sulfur impaired the resistance to debonding of the mixtures.
7. The addition of sulfur to mixtures from the three aggregate sources did not affect the values for dynamic modulus of elasticity determined at three different temperatures.
8. The addition of sulfur to the referenced aggregate mixtures reduced the tensile strength at all three test temperatures.
9. The experiment to determine the effects of moisture content in the aggregate at the time of mixing was inconclusive. Although moisture content of the aggregate at the time of mixing was determined, it was established that heating to compaction temperature dried the material and compaction improved the coating of the aggregate so that no effects on retained strength nor stability were observed at the time of testing.
10. The Deflectometer test for establishing the fatigue life of

paving mixtures showed that the addition of sulfur impaired the fatigue resistance when determined at 25°C (77°F) but had no apparent effect at 5°C (41°F).

11. The double punch tensile test and the Deflectometer test indicated that the temperature susceptibility of tensile strength was greater for the sulfur mixture with aggregate from Pit #1.
12. The reduction in both tensile strength and retained strength of the Debonding test due to the addition of sulfur are attributed to a reduced amount of asphalt in the mixture.
13. It would seem that for aggregate blends similar to those used in this study, the use of SEAR would be justified only when asphalt would be extremely scarce.
14. The investigation has shown a lack of knowledge concerned with how/why sulfur affects the characteristics of asphaltic paving mixtures and how lasting are these effects. The adverse effects noted in the study were related principally to durability and tensile strength and attributed to a reduced amount of asphalt in the mixture. It would seem that for maximum density gradation, the sulfur content of the binder should be not more than 20 percent and this amount increased as the gradation of the aggregate is opened to accommodate a greater binder content.
It is not considered good practice to replace a designed asphalt content with an equal volume of sulfur extended asphalt. In designing an SEAR mixture for a specific aggregate blend, sulfur content should be a variable in order to minimize the air void filling and asphalt reducing effects of too much sulfur in the compacted SEAR mixture.

ACKNOWLEDGEMENT

The cooperation received from the Arizona Department of Transportation is greatly appreciated. In particular we wish to acknowledge Mr. Frank McCullagh of ADOT for securing the aggregates in a most expeditious fashion and for loaning reference material at most opportune times.

Finally we sincerely appreciate the support given by the sponsorship of this work by ADOT and FHWA for we believe that many facets of using sulfur in paving mixtures need better definition and understanding.

REFERENCES

1. Bencowitz, Isaac, and Boe, E. S., "Effect of Sulfur Upon Some of the Properties of Asphalt", Proceedings, ASTM, Vol. 38, Pt. II, 1938.

2. Lee, D. Y., "Modification of Asphalt and Asphalt Paving Mixtures by Sulfur Additives", interim report, Engineering Research Institute, Iowa State University, March 1971.

3. Deme, I., "Processing of Sand-Asphalt-Sulphur Mixes", Proceedings, AAPT, Vol. 43, 1974.

4. Lee, D. Y., "Modification of Asphalt and Asphalt Paving Mixtures by Sulfur Additives", Ind. Eng. Chem., Prod. Res. Dev. 11, 3, 1975.

5. Kennepohl, G. J. A., Logan, A., and Bean, D. C.,"'Conventional' Paving Mixes with Sulfur-Asphalt Binders", Proceedings, AAPT, Vol. 44, 1975.

6. Gaw, W. J., Discussion to Kennepohl, et al., above, Proceedings, AAPT, Vol. 44, 1975.

7. Shrive, N. G., and Ward, M. A., "Some Low-Temperature Aging and Durability Aspects of Sulfur/Asphalt Concrete", STP 628, ASTM, 1976.

8. Meyer, F. R. P., Hignell, E. T., Kennepohl, G. J. A., and Hass, R. C. G.", Temperature Susceptibility Evaluation of Sulfur-Asphalt Mixtures", Proceedings, AAPT, Vol. 46, 1977.

9. Kennedy, T. W., Haas, R., Smith, P., Kennepohl, G. A., and Hignell, E. T., "Engineering Evaluation of Sulphur-Asphalt Mixtures", TRR 659, Transportation Research Board, 1977.

10. Lytton, R. L., Saylak, D., and Pickett, E., "Prediction of Sulphur-Asphalt Pavement Performance with VESYS IIM", Proceedings, Fourth International Conference on the Structural Design of Asphalt Pavements, Vol. I, Ann Arbor, Michigan, 1977.

11. Pronk, F. E., and Soderberg, A. F., "Sulphur in Asphalt Paving", Proceedings, Vol. 2, International Conference on Sulphur in Construction held in Ottawa, Ontario, 1978.

12. Lee, D. Y., "Mechanical Properties of Weathered Sulphur-Asphalt Mixtures", Proceedings, Vol. 2, International Conference on Sulphur in Construction held in Ottawa, Ontario, 1978.

13. Majidzadeh, K., and El-Mitiny, R., "The Feasibility of Using Sulfur in Bituminous Mixtures with Power Plant Bottom Ash Aggregate", Proceedings, Vol. 2, International Conference on Sulphur in Construction held in Ottawa, Ontario, 1978.

14. Bukowski, J. R., "Sulphur in Pavement Construction--A Summary Report", The Asphalt Institute, 1978.

15. Pickett, D. E., Saylak, D., Lytton, R. L., Conger, W. E., Newcomb, D., and Schapery, R. A., "Extension and Replacement of Asphalt Cement with Sulfur", Report No. FHWA-RD-78-95, Federal Highway Administration, 1978.

16. Izatt, J. O., "Sulphur-Extended-Asphalt Field Trials MH 153 Brazos County, Texas", FHWA-TS-80-214, Federal Highway Administration, 1979.

17. Smith, R. W., "An Update on Sulphur-Based Flexible Pavement Construction", Paving Forum, National Asphalt Pavement Association, 1979.

18. Fromm, H. J., and Kennepohl, G. J. A., "Sulfur-Asphaltic Concrete on Three Ontario Test Roads", Proceedings, AAPT, Vol. 48, 1979.

19. Kennedy, T. W., and Haas, R., "Sulphur-Asphalt Pavement Technology: A Review of Progress", a paper prepared for presentation to the Transportation Research Board meeting of 1980.

20. Bean, D., Kennepohl, G., and Haas, R., "Properties of Sulphur-Asphalt Mixes and the Effects of Mix Production", a paper prepared for presentation to the Transportation Research Board meeting of 1980.

21. Al-Otaishan, A. T. A., and Terrel, R. L., "Material Characteristics and Predicted Performance of Sulphur-Asphalt Mixtures from In-Service Pavements", Proceedings, AAPT, Vol. 49, 1980.

22. Jimenez, R. A., and Stokes, K. J., "Effects of Heat and Air on the Viscosity of Sulfur-Asphalt Mixtures", a paper prepared for presentation to the AAPT meeting of 1981.

23. Lahue, S. P., and Botelho, F. V., "Sulfur Extended Asphalt", Civil Engineering, ASCE, May 1981.

24. The Merck Index, Sixth edition, 1952.

25. California Test 303, Testing Manual, California Department of Transportation.

26. Supplemental to Standard Specifications for Road and Bridge Construction, Arizona Department of Transportation, 1978.

27. Mix Design Methods for Asphalt Concrete, MS-2, The Asphalt Institute, 1974.

28. Jimenez, R. A., "Testing for Debonding of Asphalt from Aggregates", Research Report Project HPR-1-10(123) submitted to the Arizona Highway Department, 1973.

29. Scott, Noel R., and Ritter, John B., "Field and Laboratory Evaluation of Debonding Test Procedures", Report Number 1980-NSI, Arizona Department of Transportation, March 1980.

30. Jimenez, R. A., "Structural Design of Asphalt Pavements for Arizona", Research Report Project HPR-1-12(142) submitted to the Arizona Department of Transportation, 1975.

31. White, W., "Relationship Between Values of Dynamic and Resilient Modulus for Asphaltic Concrete", CE 200 Project Report, University of Arizona, 1978.

32. Sonderegger, P. E., "Residual Moisture in Asphaltic Concrete Mixtures", Proceedings, AAPT, Vol. 30, 1961.

33. Jimenez, R. A., "Fatigue Testing of Asphaltic Concrete Slabs", STP 508, ASTM, 1971.

34. Hicks, C. R., Fundamental Concepts in the Design of Experiments, Second Edition, Holt, Rinehart, and Winston, 1973.

35. Jimenez, R. A., Discussion to presentation by C. L. Monismith, Proceedings, AAPT, Vol. 49, 1980.

APPENDIX

List of Tables

TABLE A-1. CHARACTERISTICS OF ASPHALT CEMENTS, ADOT SPECIFICATIONS [26].

Test on 75 min RTFC Residue	AR-2000	AR-4000
Viscosity, abs 140°F, p	1,500-2,500	3,000-5,000
kin 275°F, cs, min	200	275
Penetration, 77°F, 100g, 5 sec, min	40	25
Percent of original penetration, 77°F, min	40	45
Ductility, 77°F, cm, min	100	75
Test on Original Asphalt		
Flash point, Pensky Marten, °F, min	425	440
Solubility in trichloroethylene, %, min	99	99
Measured specific gravity 77°F/77°F	1.020	1.019

10 p = 1 Pa-s
°F = 32 + 1.8°C

TABLE A-2. PHYSICAL PROPERTIES OF AGGREGATES

Aggregate	Pit #1 Phoenix	Pit #2 Tucson Original	Pit #2 Tucson Modified	Pit #3 Holbrook
Gradation				
Sieve Size	Percent Passing			
1" (25.4 mm)	100	100	100	100
3/4" (19.0 mm)	94	100	100	86
3/8" (9.5 mm)	71	91	93	58
#4	50	64	65	44
#8	38	52	46	34
#16	30	36	32	28
#30	22	22	21	24
#50	15	12	15	15
#100	9	8	11	6
#200	5	6	8	3
Surface Area, ft^2/lb	34.1	35.6	34.5	24.4
(m^2/kg)	(6.99)	(7.30)	(7.07)	(5.00)
Sand Equivalent	59	50	33	47
Effective S.G. for AR-2000 and for AR-4000	2.673	2.630	---	2.956

TABLE A-3. SPECIMEN CHARACTERISTICS FOR PIT #1 TESTED BY HVEEM AND MARSHALL METHODS

Binder	AR-2000			SEAR-2000				SEAR-4000				
HVEEM METHOD												
Binder Content, %	4.5	5.0	5.5	4.5	5.0	5.5	6.0	4.5	5.0	5.5	6.0	
(By Eq. Vol. of A.C.)*				3.8	4.3	4.7	5.1	3.8	4.3	4.7	5.1	
Density, pcf	150.5	151.5	151.0	152.0	152.0	152.5	153.0	150.0	152.5	153.0	153.0	
C_v,%	0.5	0.1	0.0	0.3	0.5	0.5	0.2	0.5	0.2	0.3	0.1	
Air Voids, %	3.3	1.9	1.5	3.8	3.3	2.1	1.2	5.0	2.7	1.9	1.2	
C_v,%	15.7	3.1	0.0	7.4	15.4	20.8	17.8	10.2	7.6	16.4	4.7	
Stability,	12	16	15	38	33	32	31	44	37	36	34	
C_v,%	11.7	15.3	24.0	0.0	5.2	3.1	18.0	4.8	6.9	1.6	8.6	
Cohesiometer Value	230	230	250	210	230	360	290	180	210	240	260	
C_v,%	19.5	15.3	11.8	28.7	24.9	14.5	32.7	9.8	25.7	14.8	9.5	
MARSHALL METHOD												
Binder Content, %				5.0	5.5	6.0	6.5	4.5	5.0	5.5	6.0	6.5
(By Eq. Vol. of A.C.)*				4.3	4.7	5.1	5.5	3.8	4.3	4.7	5.1	5.5
Density, pcf				148.0	150.0	150.0	151.0	147.0	146.5	147.5	151.0	151.5
C_v,%				0.2	0.3	0.5	0.5	1.2	0.3	0.4	0.5	0.6
Air Voids, %				5.7	4.0	3.5	2.1	7.0	6.6	5.3	2.7	1.7
C_v,%				3.6	8.0	13.6	21.8	16.6	4.0	6.7	20.2	31.8
Stability, lb.				1880	2240	2000	2320	2560	2180	2380	3130	3130
C_v,%				22.1	9.8	18.0	20.8	26.7	5.1	9.6	16.5	12.3
Flow, 0.01 in. (0.25 mm)				7	10	10	11	11	11	8	12	11
C_v,%				10.7	21.5	23.9	23.7	44.3	9.1	12.5	13.1	18.2

*These numbers correspond to the asphalt content having the same volume as the indicated SEA content.

1 pcf = 16.03 kg/m³
1 lbf = 4.44 N

$$C_v = \frac{\sigma}{\bar{x}} \times 100$$

TABLE A-4. SPECIMEN CHARACTERISTICS FOR PIT #2 TESTED BY HVEEM AND MARSHAL METHODS

Binder	AR-2000				SEAR-2000					SEAR-4000				
					HVEEM METHOD									
Binder Content, %	5.0	5.5	6.0	6.5	5.0	5.5	6.0	6.5	7.0	5.5	6.0	6.5	7.0	
(By Eq. Vol. of A.C.)*					4.3	4.7	5.1	5.5	6.0	4.7	5.1	5.5	6.0	
Density, pcf	144.5	145.0	145.5	146.5	144.0	145.0	145.5	145.5	146.0	143.5	144.5	145.0	146.0	
C_v,%	0.6	0.3	0.2	0.1	0.3	0.6	0.2	0.3	0.4	0.5	0.1	0.3	0.1	
Air Voids, %	5.2	4.0	2.9	1.6	6.8	5.7	4.7	4.2	3.3	6.5	5.4	4.5	3.2	
C_v,%	11.7	6.3	5.2	3.7	3.7	9.1	5.3	6.9	10.8	7.2	1.1	11.0	3.6	
Stability,	18	19	17	15	32	34	35	34	28	26	24	25	26	
C_v,%	6.3	5.3	5.9	3.9	1.8	6.9	7.1	7.8	2.1	15.2	7.1	24.4	5.8	
Cohesiometer Value	150	210	170	160	210	230	270	310	260	220	250	250	270	
C_v,%	7.2	12.3	6.9	7.1	8.8	9.3	7.5	18.2	13.8	7.7	12.0	13.5	12.2	
										MARSHALL METHOD				
Binder Content, %					5.5	6.0	6.5	7.0	7.5	5.5	6.0	6.5	7.0	7.5
(By Eq. Vol. of A.C.)*					4.7	5.1	5.5	6.0	6.4	4.7	5.1	5.5	6.0	6.4
Density, pcf					137.5	139.0	140.5	141.0	141.5	137.5	138.0	139.5	142.0	142.5
C_v,%					0.4	0.5	0.2	0.5	0.3	0.2	0.6	0.2	0.0	0.8
Air Voids, %					10.6	9.1	7.6	6.6	5.8	10.6	9.7	8.1	6.2	5.2
C_v,%					3.6	6.2	2.6	6.9	5.2	1.9	5.7	1.9	0.0	14.6
Stability, lb.					770	1200	1300	1310	1300	1610	1580	1500	2030	2040
C_v,%					9.2	6.5	8.9	1.5	7.2	12.4	7.6	7.9	0.9	8.3
Flow, 0.01 in. (0.25 mm)					10	8	8	9	9	10	11	8	15	13
C_v,%					0.0	18.3	18.3	11.1	13.3	10.0	14.0	18.1	9.5	27.7

*These numbers correspond to the asphalt content having the same volume as the indicated SEA content.

1 pcf = 16.03 kg/m³
1 lbf = 4.44 N

TABLE A-5. SPECIMEN CHARACTERISTICS FOR PIT #3 TESTED BY HVEEM AND MARSHALL METHODS

Binder	AR-2000				SEAR-2000				SEAR-4000			
					HVEEM METHOD							
Binder Content, %	4.0	4.5	5.0	5.5	4.5	5.0	5.5	6.0	4.0	4.5	5.0	5.5
(By Eq. Vol. of A.C.)*					3.8	4.3	4.7	5.1	3.4	3.8	4.3	4.7
Density, pcf	165.5	167.0	167.5	168.0	167.0	167.5	167.5	169.5	166.0	166.0	167.0	168.0
C_v,%	0.4	0.1	0.2	0.5	0.4	0.3	0.7	0.6	0.9	0.7	0.3	0.2
Air Voids, %	3.4	1.8	0.7	0.0	3.4	2.2	1.6	0.0	4.7	3.8	2.6	1.4
C_v,%	11.0	6.5	31.2	--	11.8	13.7	44.8	--	16.9	16.4	11.3	14.3
Stability,	27	24	22	16	28	26	24	29	34	32	27	25
C_v,%	7.6	11.0	12.0	21.5	15.6	9.6	15.6	12.4	13.5	7.3	5.7	25.0
Cohesiometer Value	120	200	220	240	160	190	230	250	140	160	160	250
C_v,%	27.4	19.4	31.7	21.9	19.7	14.1	8.9	14.4	19.2	20.6	28.4	37.7
							MARSHALL METHOD					
Binder Content, %					4.5	5.0	5.5		4.0	4.5	5.0	5.5
(By Eq. Vol. of A.C.)*					3.8	4.3	4.7		3.4	3.8	4.3	4.7
Density, pcf					162.0	163.5	163.0		162.5	162.5	163.0	163.5
C_v,%					0.5	0.9	0.2		0.4	0.2	0.3	0.9
Air Voids, %					6.0	4.6	3.6		6.7	5.8	4.9	4.0
C_v,%					7.5	18.1	4.8		5.2	3.0	5.4	21.8
Stability, lb.					1560	1730	1970		1780	1560	1630	1730
C_v,%					8.0	17.8	20.1		17.4	12.7	21.3	15.3
Flow, 0.01 in. (0.25 mm)					9	9	12		11	10	9	10
C_v,%					11.1	29.4	17.8		10.8	11.2	13.3	26.5

*These numbers correspond to the asphalt content having the same volume as the indicated SEA content.

1 pcf = 16.03 kg/m³
1 lbf = 4.44 N

$C_v = \frac{\sigma}{\bar{x}} \times 100$

TABLE A-6. EFFECT OF COMPACTION TEMPERATURE ON DEBONDING AND MARSHALL TEST VALUES ON A MIXTURE OF SEAR AND PIT #1 AGGREGATE

Compaction Temperature C (F)	107 (225)	121 (250)	135 (275)
	DEBONDING TEST - SEAR @ 5.1%		
Density, pcf	151.5	152.5	152.5
C_v,%	1.0	0.3	0.8
Air Voids, %	3.4	2.8	2.7
C_v,%	27.1	11.1	29.1
Wet Strength, psi	114	111	163
C_v,%	2.5	19.0	7.3
Dry Strength, psi	132	120	155
C_v,%	3.4	4.4	4.3
Retained Strength, %	86	92	106
	MARSHALL TEST - SEAR @ 5.6%		
Density, pcf	146.5	148.5	149.0
C_v,%	0.3	0.2	0.1
Air Voids, %	5.9	4.6	4.3
C_v,%	3.9	5.4	1.3
Stability, lb	1680	1820	1790
C_v,%	12.6	11.3	12.9
Flow, 0.01 in. (0.25 mm)	8	7	7
C_v,%	13.9	34.3	28.6

1 pcf = 16.03 kg/m³
1 psi = 6.89 kPa
1 lbf = 4.44 N

$$C_v = \frac{\sigma}{\bar{x}} \times 100$$

TABLE A-6-1. ANALYSIS OF VARIANCE FOR COMPACTION TEMPERATURE STUDY--TABLE A-6.

Debonding Air Voids

Source	df	SS	MS	F	Significant?
Temperature	2	1.6578	0.829	1.626	No
Error	15	7.6466	0.510		
Total	17	9.3044			

Debonding Wet Strength

Source	df	SS	MS	F	Significant?
Temperature	2	5188.22	2594.1	13.17	Yes
Error	6	1182.00	197.0		
Total	8	6370.72			

Debonding Dry Strength

Source	df	SS	MS	F	Significant?
Temperature	2	1852.67	926.33	30.00	Yes
Error	6	185.33	30.88		
Total	8	2038.00			

Marshall Air Voids

Source	df	SS	MS	F	Significant?
Temperature	2	4.340	2.170	54.25	Yes
Error	6	0.240	0.040		
Total	8	4.580			

Marshall Stability

Source	df	SS	MS	F	Significant?
Temperature	2	154,400	77,200	1.503	No
Error	6	308,200	51,367		
Total	8	462,600			

Note: All tests for significance performed at a 95% confidence level.

TABLE A-7. EFFECTS OF SULFUR AND ANTI-STRIP ON DEBONDING OF PIT #1 AGGREGATE

Binder	AR-2000			AR-2000 + 1% Anti-Strip			SEAR-2000			SEAR-2000 + 1% Anti-Strip		
Binder Content, %	4.0	4.5	5.0	4.0	4.5	5.0	4.5	5.0	5.5	4.5	5.0	5.5
(By Eq. Vol. of A.C.)*							3.8	4.3	4.7	3.8	4.3	4.7
Density, pcf	151.0	152.0	153.0	151.0	152.0	152.5	151.0	152.5	154.0	151.0	153.5	153.5
C_v,%	0.6	0.6	0.3	0.4	0.7	0.3	0.5	0.4	0.3	0.3	0.5	0.5
Air Void, %	3.5	2.2	1.0	3.5	2.4	1.1	4.2	2.9	1.4	4.3	2.3	1.7
C_v,%	16.2	26.9	31.8	11.6	29.2	28.3	11.8	11.4	23.6	6.9	20.2	29.3
Wet Strength, psi	128	149	148	148	146	146	96	105	108	100	124	128
C_v,%	8.4	25.1	16.1	4.1	12.2	12.6	5.5	15.8	15.3	10.0	17.0	18.8
Dry Strength, psi	148	168	136	172	155	148	123	130	123	130	148	127
C_v,%	12.0	10.3	5.1	7.1	11.5	2.1	8.5	4.1	18.9	7.1	17.6	4.7
Retained Strength, %	86	89	109	86	94	99	78	81	88	77	84	101

*These numbers correspond to the asphalt content having the same volume as the indicated SEA content.

1 pcf = 16.03 kg/m³
1 psi = 6.89 kPa

$$C_v = \frac{\sigma}{\bar{x}} \times 100$$

TABLE A-7-1. ANALYSIS OF VARIANCE FOR DEBONDING STUDY--TABLE A-7.

Wet Strength

Source	df	SS	MS	F	Significant?
Binder Content	2	1,576.17	788.08	2.42	No
Anti-Strip Additive	1	831.36	831.36	2.56	No
Sulfur	1	10,370.03	10,370.03	31.90	Yes
Error	31	10,079.19	325.14		
Total	35	22,856.75			

Dry Strength

Source	df	SS	MS	F	Significant?
Binder Content	2	1,736.06	868.03	3.36	Barely
Anti-Strip Additive	1	702.25	702.25	2.72	No
Sulfur	1	4,117.36	4,117.36	15.96	Yes
Error	31	7,999.97	258.06		
Total	35	14,555.64			

Note: All tests for significance performed at a 95% confidence level.

TABLE A-8. EFFECTS OF SULFUR AND ANTI-STRIP ON DEBONDING OF MODIFIED PIT #2 AGGREGATE

Binder	AR-2000			SEAR-2000		SEAR-2000 + 1% Anti-Strip	
Binder Content, %	5.0	5.5	6.0	6.0	6.5	6.0	6.5
(By Eq. Vol. of A.C.)*				5.1	5.5	5.1	5.5
Density, pcf	141.5	142.5	143.5	143.5	145.5	143.0	143.5
C_v,%	0.5	0.3	0.6	0.2	0.2	0.8	0.2
Air Void, %	6.9	5.8	4.2	6.0	4.4	6.5	5.7
C_v,%	6.6	4.5	14.5	2.5	3.6	11.5	3.9
Wet Strength, psi	59	104	116	36	102	44	80
C_v,%	10.4	4.9	4.2	16.6	6.7	1.3	3.3
Dry Strength, psi	98	55	77	89	53	86	53
C_v,%	9.3	5.9	2.0	7.4	2.9	11.5	14.7
Retained Strength, %	60	53	66	41	52	41	66

*These numbers correspond to the asphalt content having the same volume as the indicated SEA content.

1 pcf = 16.03 kg/m³
1 psi = 6.89 kPa

$$C_v = \frac{\sigma}{\bar{x}} \times 100$$

TABLE A-9. EFFECTS OF SULFUR AND TEST TEMPERATURE ON TENSILE PROPERTIES OF MIXTURES OF THREE AGGREGATES.

Test Temperature C (F)	-5 (23)	10 (50)	25 (77)	-5 (23)	10 (50)	25 (77)
			Pit #1			
Binder	AR-2000 @ 4.2%			SEAR-2000 @ 4.8%		
Density, pcf	151.0	151.0	151.5	152.0	151.0	151.5
C_v,%	0.1	0.4	0.3	0.4	0.2	0.3
Air Voids, %	3.6	3.3	3.2	3.4	4.2	3.8
C_v,%	1.6	13.2	7.9	12.8	3.6	8.4
Tensile Strength, psi	562	460	169	555	414	127
C_v,%	11.4	8.4	2.2	10.8	9.1	10.1
Dynamic Modulus, ksi	299.3	237.7	203.7	251.3	259.0	184.3
C_v,%	18.8	16.9	27.3	6.6	13.6	19.2
			Pit #2			
Binder	AR-2000 @ 5.9%			SEAR-2000 @ 7.0%		
Density, pcf	142.0	142.5	143.0	144.0	144.0	145.0
C_v,%	0.8	0.2	0.7	0.2	0.2	0.5
Air Voids, %	5.4	5.2	4.9	4.9	4.9	4.2
C_v,%	14.0	4.0	13.0	4.2	4.3	11.9
Tensile Strength, psi	453	369	106	472	327	96
C_v,%	2.8	9.6	7.2	2.7	3.9	5.7
Dynamic Modulus, ksi	275.7	289.7	203.7	362.0	316.7	195.3
C_v,%	9.7	18.0	18.4	25.3	18.2	19.8
			Pit #3			
Binder	AR-2000 @ 4.1%			SEAR-2000 @ 4.6%		
Density, pcf	166.0	166.5	167.0	167.5	166.5	167.5
C_v,%	0.5	0.4	0.5	0.4	0.5	0.4
Air Voids, %	2.9	2.6	2.5	3.1	3.5	3.0
C_v,%	15.0	15.4	20.0	12.4	14.0	12.5
Tensile Strength, psi	532	424	177	554	397	127
C_v,%	18.2	10.9	12.4	12.8	18.4	21.4
Dynamic Modulus, ksi	287.3	216.7	203.7	363.3	245.0	187.7
C_v,%	52.6	38.8	9.6	15.0	49.3	6.7

1 pcf = 16.03 kg/m³
1 psi = 6.89 kPa
1 ksi = 1000 psi = 6.89 MPa

$$C_v = \frac{\sigma}{\bar{x}} \times 100$$

TABLE A-9-1. ANALYSIS OF VARIANCE FOR TENSILE PROPERTIES STUDY--TABLE A-9.

Dynamic Modulus

Source	df	SS	MS	F	Significant?
Temperature	2	132,435	66,218	15.49	Yes
Pits	2	13,843	6,921	1.62	No
Sulfur	1	1,262	1,262	0.30	No
Error	48	205,139	4,274		
Total	53	352,679			

Tensile Strength

Source	df	SS	MS	F	Significant?
Temperature	2	1,413,988	706,994	416.12	Yes
Pits	2	61,592	30,796	18.13	Yes
Sulfur	1	9,074	9,074	5.34	Yes
Error	48	81,531	1,699		
Total	53	1,566,185			

Newman-Keuls Test: $S_{\bar{P}} = \sqrt{\frac{1699}{18}} = 9.72$

	P:	2	3
Least Significant Range:		28	33

Pit #	2		3		1
Mean	304	$\xleftrightarrow{64}$ Different	368	$\xleftrightarrow{13}$ Same	381

304 $\xleftrightarrow{77}$ 381: Different

Conclusion: Tensile strength for Pit #2 is significantly lower than Pit #1 or Pit #3.

Note: All tests for significance performed at a 95% confidence level.

TABLE A-10. EFFECT OF MOISTURE CONTENT IN THE PIT #1 AGGREGATE AT THE TIME OF MIXING AT 121°C (250°F) ON DEBONDING AND MARSHALL TEST VALUES.

Debonding Test SEAR-2000 @ 5.1%				Marshall Test SEAR-2000 @ 5.6%			
Moisture Content, %	Air Voids, %	Strength Wet, psi	Strength Dry, psi	Moisture Content, %	Air Voids, %	Stability, lbs	Flow 0.01 in.
0	2.1	--	125	0	4.0	2020	8
0	3.1	--	128	0	3.8	2200	11
0	2.3	--	140	0	4.5	2380	11
0	3.1	101	--	0.4	4.6	1130	11
0	1.9	113	--	0.4	5.7	930	10
0	2.9	116	--	0.4	4.1	1340	10
0.5	2.2	104	--	0.9	2.6	2630	13
0.8	1.1	--	126	0.9	3.0	2510	14
0.8	1.2	--	156	0.9	4.6	1800	10
0.8	0.5	110	--	2.2	3.4	2250	13
1.0	1.3	--	89	2.2	2.3	2990	15
1.0	0.5	136	--	2.2	2.8	2630	14
1.0	2.0	124	--	2.2	2.2	2450	9
1.2	0.9	--	105	2.2	2.7	2030	11
1.2	0.4	127	--	2.2	2.4	2750	11
1.2	0.8	130	--				
1.7	2.0	--	113				
1.7	1.4	--	113				
1.7	2.1	129	--				
3.1	1.4	--	117				
3.1	0.8	--	137				
3.1	2.2	124	--				

TABLE A-11. EFFECT OF MOISTURE CONTENT IN THE PIT #1 AGGREGATE AT THE TIME OF MIXING AT 93°C (200°F) ON DEBONDING TEST VALUES. SEAR-2000 @ 5.1%

Moisture Content, %	Air Voids, %	Strength	
		Wet, psi	Dry, psi
0	2.9	--	95
0	3.5	--	85
0	4.2	--	93
0	3.8	87	--
0	2.6	107	--
0	3.7	71	--
0.4	3.7	--	89
0.4	3.2	--	102
0.4	4.2	99	--
0.5	2.2	--	92
0.5	3.1	--	117
0.5	3.1	87	--
0.6	1.4	--	112
0.6	2.8	--	121
0.6	2.0	93	--
0.6	2.0	71	--
0.6	2.8	83	--
0.6	2.9	96	--
0.9	1.8	--	95
0.9	3.3	80	--
0.9	1.8	92	--
1.0	3.3	--	81
1.0	1.8	--	91
1.0	2.1	81	--
1.7	2.7	--	93
1.7	2.5	--	120
1.7	2.6	--	109
1.7	3.3	62	--
1.7	2.5	85	--
1.7	2.5	93	--

TABLE A-12. DEFLECTOMETER FATIGUE TESTING RESULTS FOR PIT #1 AGGREGATE AT TWO TEMPERATURES. $\sigma_T = I_o N^{-b}$

AR-2000 @ 4.2%				SEAR-2000 @ 4.9%			
Thickness in.	E_D ksi	σ_T psi	N Reps in 10^3	Thickness in.	E_D ksi	σ_T psi	N Reps in 10^3
Test Temperature, 25°C (77°F)							
1.57	58.5	124	5.0	1.57	35.5	128	2.5
1.57	46.0	126	4.0	1.58	42.0	125	4.0
1.58	63.0	122	4.0	1.59	31.0	125	1.5
2.09	45.5	69	25.0	2.10	38.5	69	7.5
2.09	54.5	69	15.0	2.10	53.5	68	8.0
2.10	53.5	68	12.5	2.71	25.0	41	120.0
2.70	25.5	41	140.0	2.71	31.0	41	100.0
2.72	41.0	40	140.0	2.74	40.0	40	70.0
2.73	40.5	40	120.0				

$\sigma_T = 1622\ N^{-0.3154}$ $\quad$ $R^2 = 0.957$ $\quad$ n = 9

$\sigma_T = 1097\ N^{-0.2900}$ $\quad$ $R^2 = 0.921$ $\quad$ n = 8

AR-2000 @ 4.2%				SEAR-2000 @ 4.9%			
Test Temperature, 5°C (41°F)							
1.57	128.5	140	700	1.60	152.0	151	450
1.60	152.0	151	350	1.59	154.5	153	450
2.07	93.5	106	1,500	1.59	206.0	153	400
2.07	70.0	106	1,700	2.06	95.0	107	1,600
2.07	93.5	106	1,400	2.06	95.0	107	1,700
				2.06	95.0	107	1,500

$\sigma_T = 4005\ N^{-0.2542}$ $\quad$ $R^2 = 0.940$ $\quad$ n = 5

$\sigma_T = 4980\ N^{-0.2687}$ $\quad$ $R^2 = 0.994$ $\quad$ n = 6

Combined Data

$\sigma_T = 4665\ N^{-0.2646}$

$R^2 = 0.970$

n = 11

1 ksi = 1000 psi = 6.89 MPa

1 in. = 25.4 mm

List of Figures

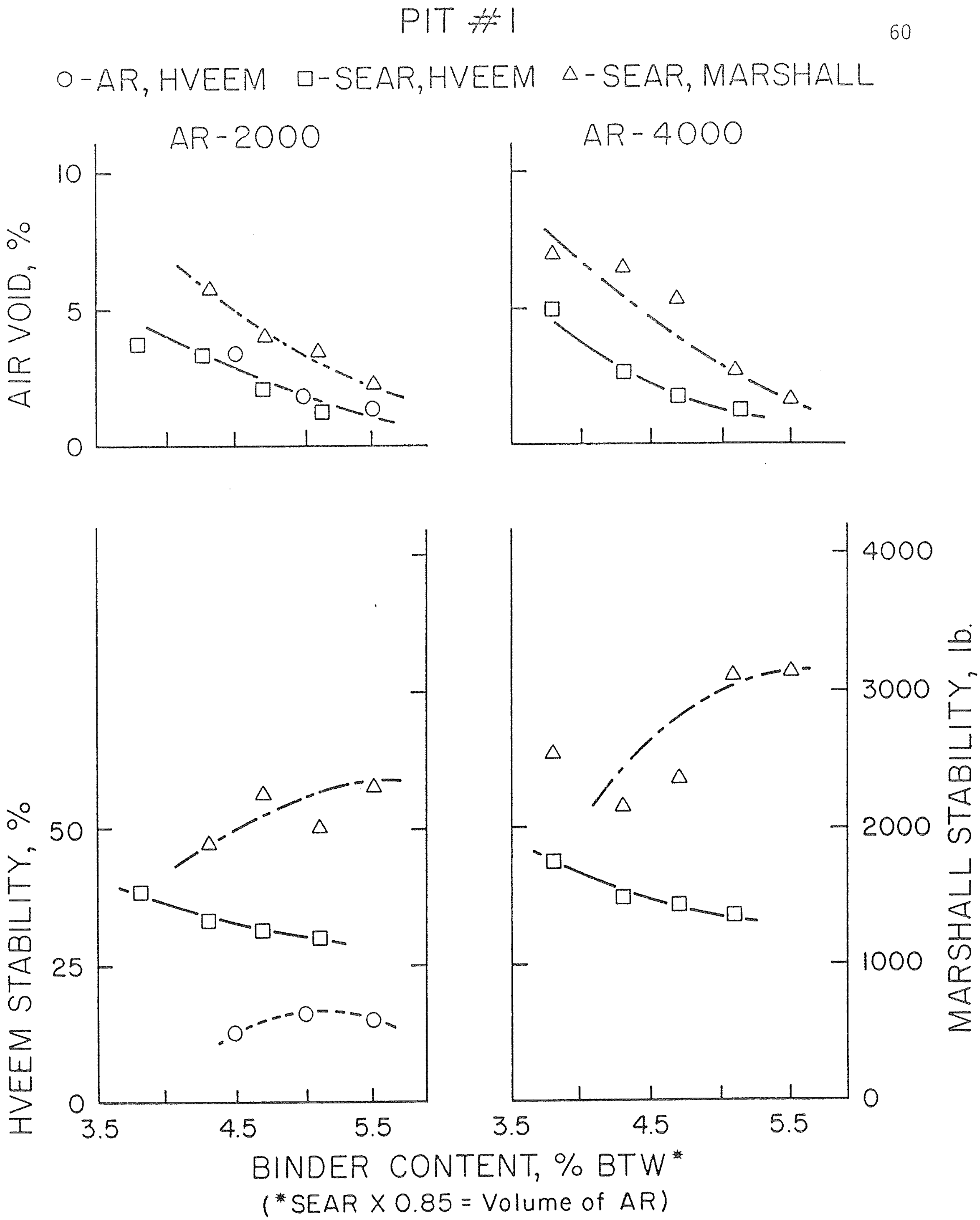

Figure 1. Effects of Binder Content on Hveem and Marshall Stabilities and Voids

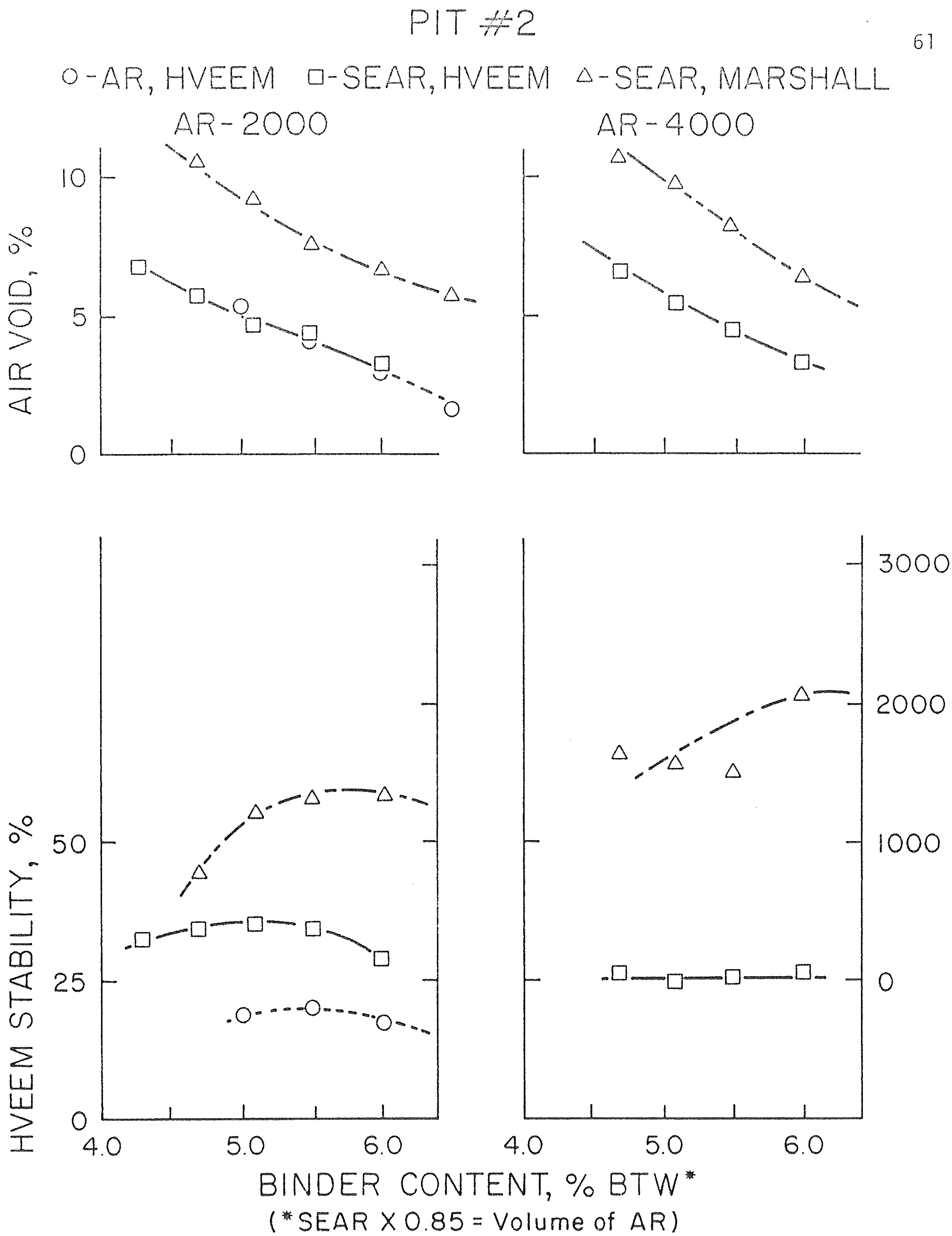

Figure 2. Effects of Binder Content on Hveem and Marshall Stabilities and Voids.

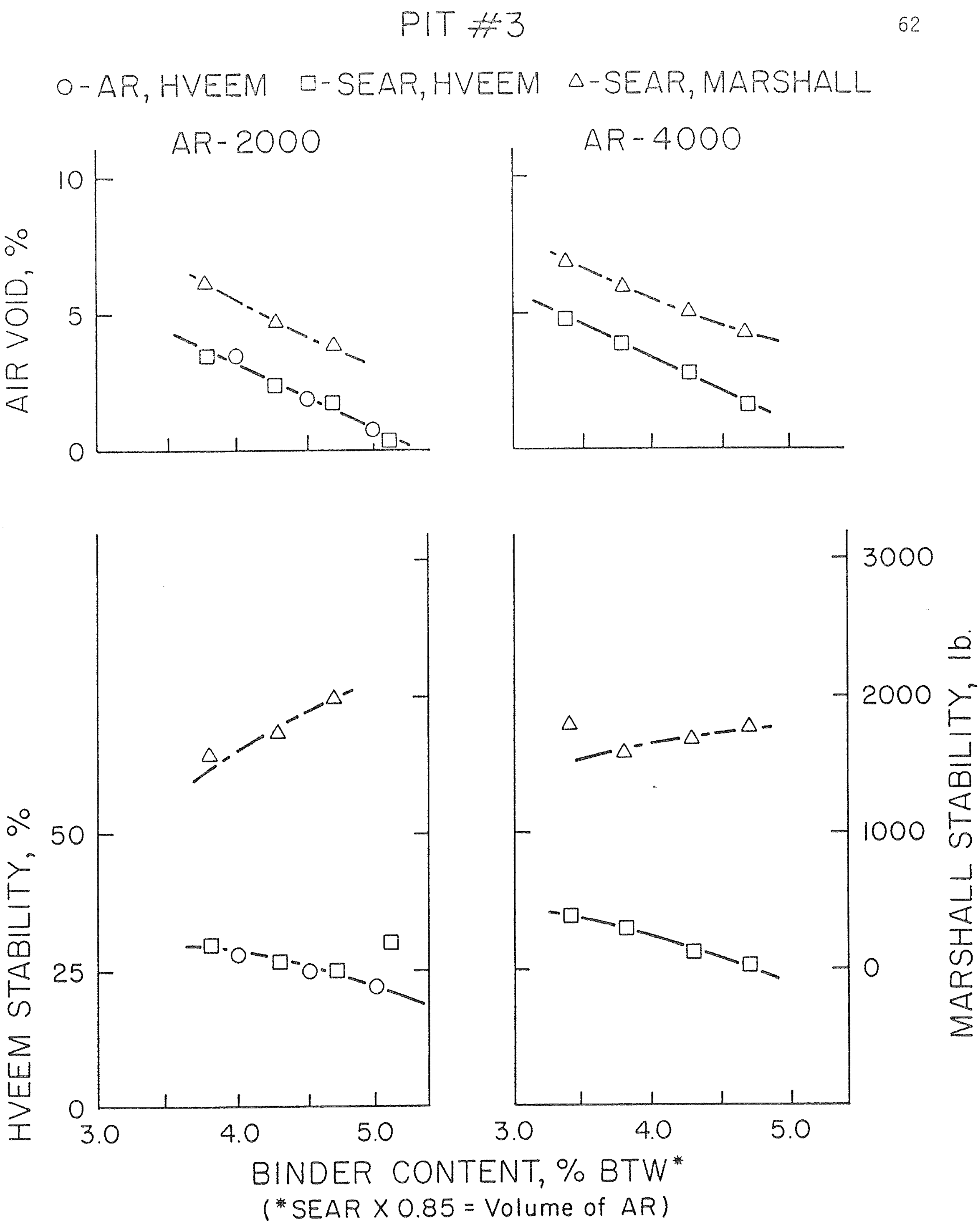

Figure 3. Effects of Binder Content on Hveem and Marshall Stabilities and Voids

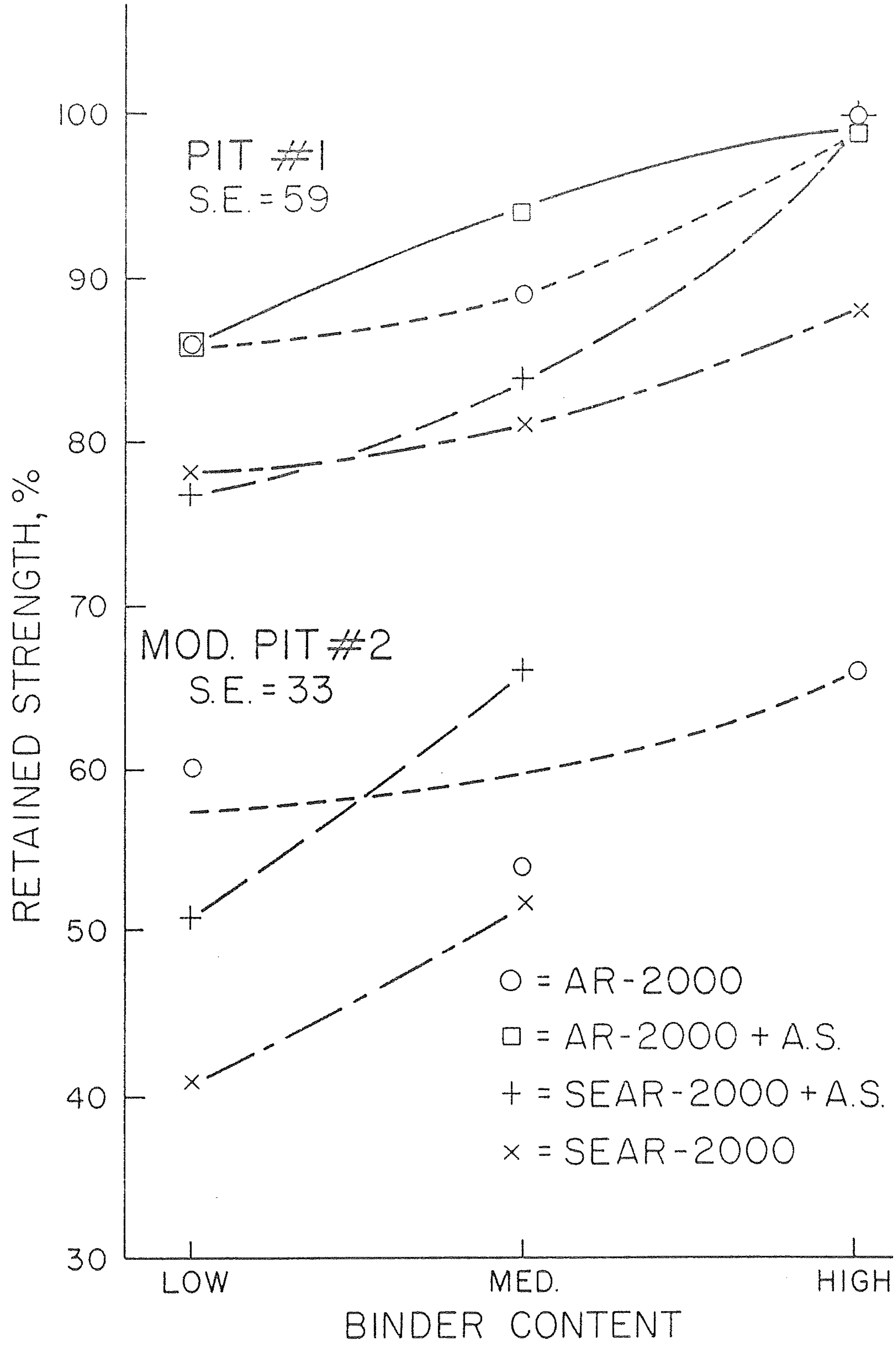

Figure 4. Effects of Contents of Sulfur and Anti-strip Binders on Debonding Test

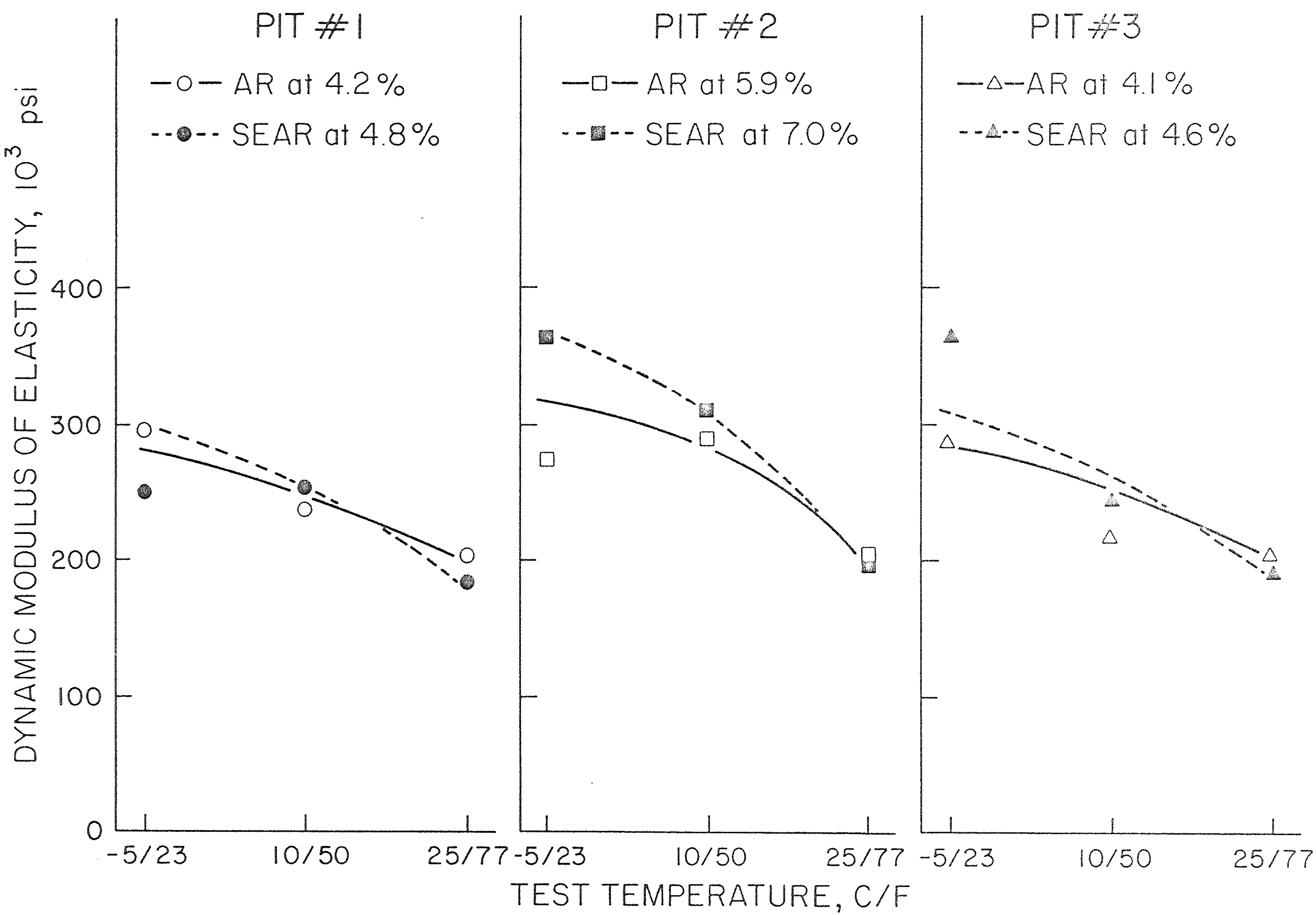

Figure 5. Effects of Temperature on Elasticity of AR-2000 Mixtures

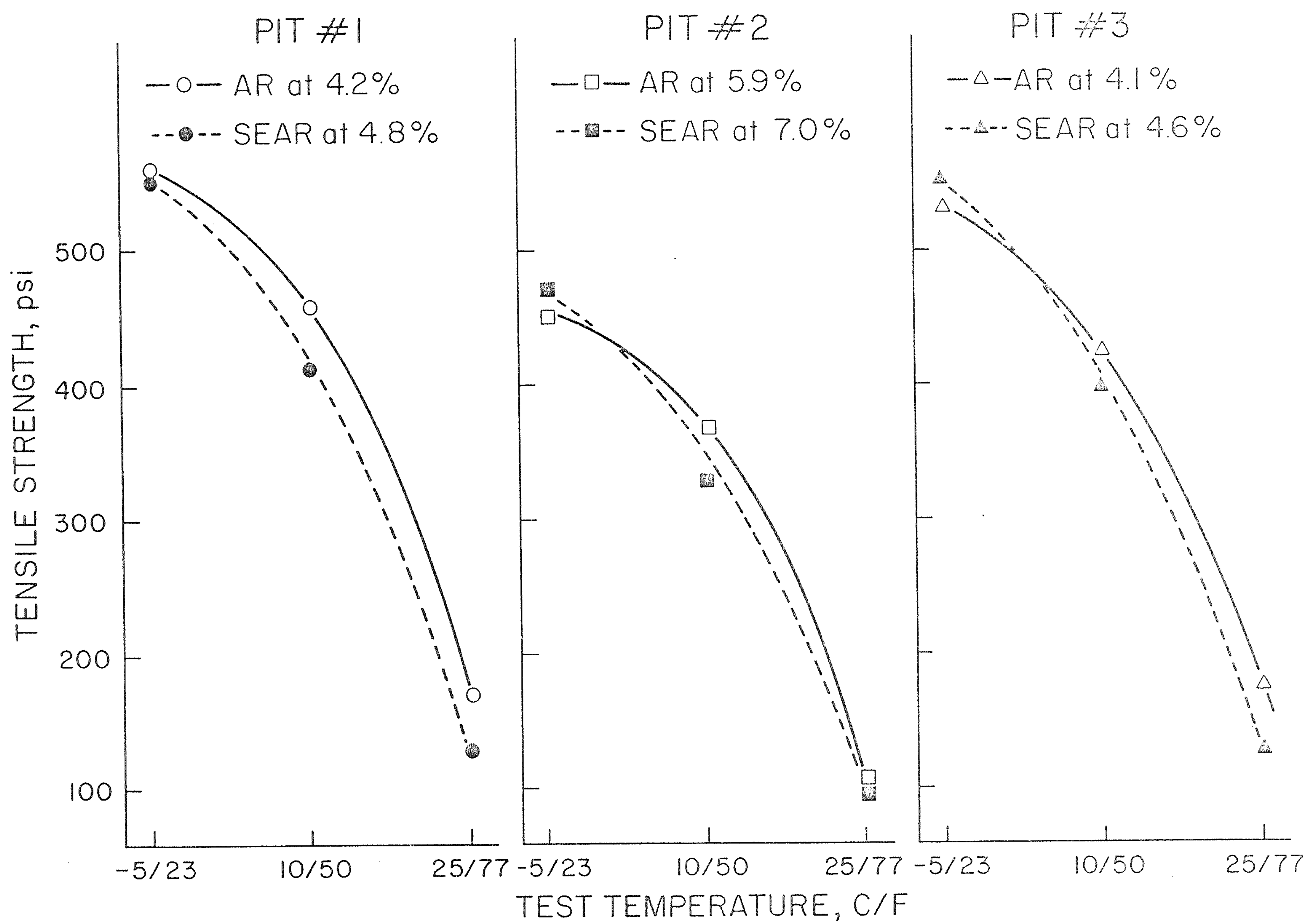

Figure 6. Effects of Temperature on Tensile Strength of AR-2000 Mixtures

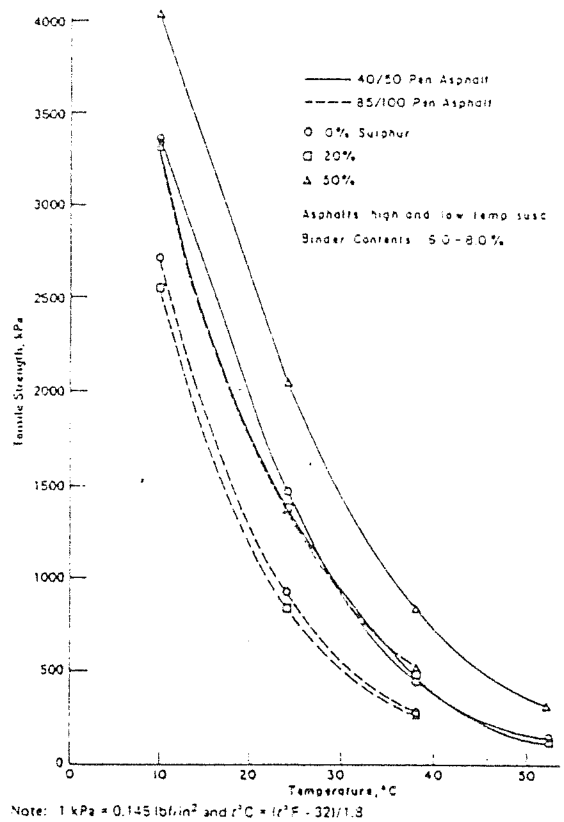

Figure 7. Relation Between Tensile Strength and Temperature (Reference 9)

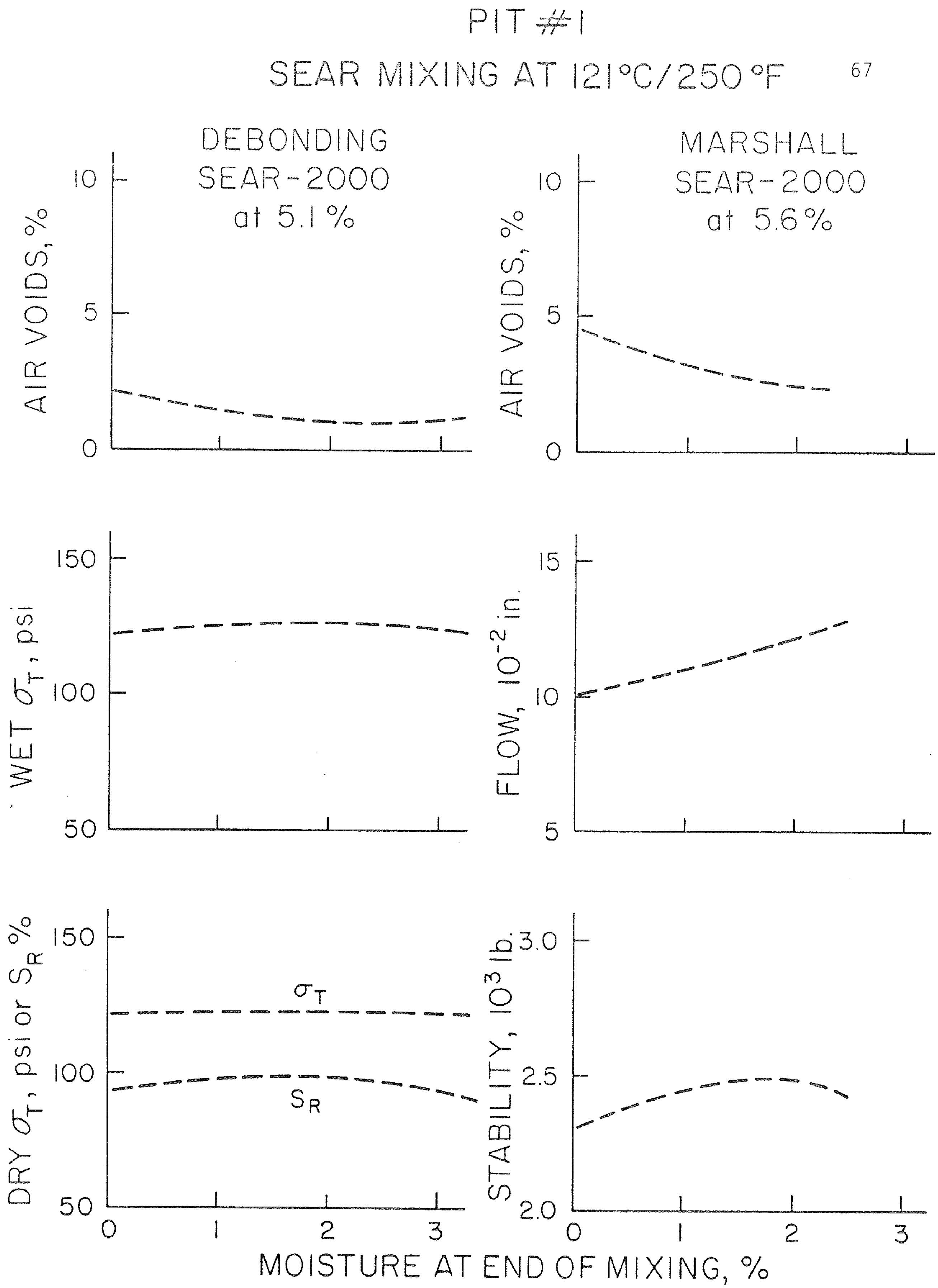

Figure 8. Effects of Mixing Moisture on Debonding and Marshall Values

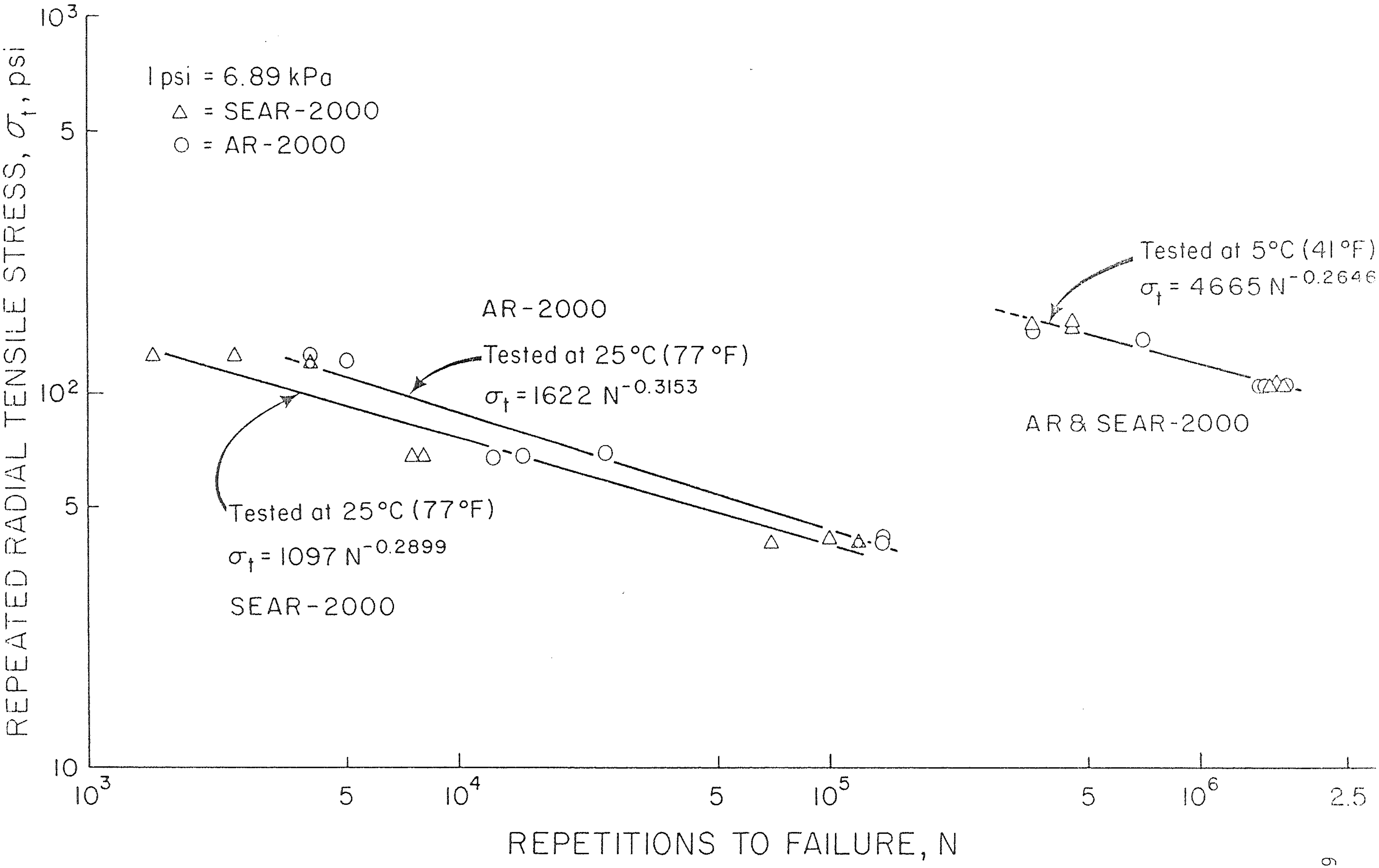

Figure 9. Relationship Between Repeated Tensile Stress and Repetitions to Cause Failure.